

**From:** [Anne Kania](#)  
**To:** [DEQ WQP Admin](#)  
**Subject:** Comments on Circular DEQ-12B  
**Date:** Tuesday, April 01, 2014 12:47:53 PM  
**Attachments:** [DEQ Response-BioHaven.docx](#)  
[Dodkins report swansea.pdf](#)  
[Summaries sorted by type and date 4-01-14.pdf](#)

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Dear Carrie,

Please find attached a word document containing comments on the Variances Circular, and two supporting pdf documents.

Thank you,  
Anne Kania

**Anne Kania**

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April 1, 2014

To Whom It May Concern:

Re: Circular DEQ-12A Nutrient Standards and DEQ-12B Variances

Thank you for the opportunity to comment on the proposed new Nutrient Standards and Variances. We appreciate the work DEQ is doing to protect the environment for future generations, especially our aquatic environment.

I am making these comments on behalf of BioHaven, Inc., a licensee of Floating Island International (FII). We are based in Montana and handle the business of sales and marketing in the Rocky Mountain States and Western Canada, in partnership with FII's other four licensed manufacturers and our network of distribution partners in Montana and the surrounding states.

We are the sole distributors of BioHaven floating islands, a type of constructed wetland that in our opinion can be considered a viable alternative solution to assist Montanans in meeting the proposed nutrient standards.

I wish to comment specifically on the Variances circular.

We note that, "Montana's Legislature adopted laws (e.g., §75-5-313, MCA) allowing for the achievement of the standards over time via the variance procedures found here in Circular DEQ-12B. *This approach should allow time for nitrogen and phosphorus removal technologies to improve and become less costly, and to allow time for nonpoint sources of nitrogen and phosphorus pollution to be better addressed.*"

We believe that such a nitrogen and phosphorus removal technology is available now. I would like to take this opportunity to present some background information that will enable it be placed on the list of approved alternative technologies to be consulted whenever a variance is applied for.

BioHaven floating treatment wetlands (FTWs) offer an *in situ* solution that can directly augment the nutrient removal process in lagoons; or alternatively, can be applied "further up" in the watershed, to mitigate the total load within the watershed, and reduce the downstream affects on beneficial uses. The possibilities of applying this

technology in Big Timber, for example, to limit the nutrient load coming downstream to Billings, spreads the economic impact between multiple communities, and provides a template for credits to be traded within and beyond the watershed.

A summary report on FTWs, attached to this email, is the most comprehensive literature review of FTWs to date, published jointly by Swansea University (Wales) and Seacams in March 2014. BioHaven Inc.'s Montana-based technology is clearly identified as the industry leader. There is no question that FTWs are an effective and affordable means to treat point source and nonpoint source waste waters.

The website [www.floatingislandinternational.com](http://www.floatingislandinternational.com) contains numerous case studies and research papers testifying to the efficacy of BioHaven floating islands. A complete list of publications is attached for your reference.

Thank you again for the opportunity to comment. I look forward to being able to serve Montanans, and the life and waters that depend on our stewardship, through deployment of cost-effective and sustainable technology.

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Swansea University  
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SEACAMS Swansea University

## *Enterprise Assist:*

# Floating Treatment Wetlands (FTWs) in Wastewater Treatment: Treatment efficiency and potential benefits of activated carbon.

**I Dodkins & AF Mendzil**

March 2014

Prepared for: FROG Environmental Ltd, Ban y Berllan,  
Llansadwrn, Llanwrda, SA19 8NA.



Sustainable Expansion of the Applied Coastal  
And Marine Sectors (SEACAMS)

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Literature Review:

## **Floating Treatment Wetlands (FTWs) in Wastewater Treatment: Treatment efficiency and potential benefits of activated carbon.**

Dr. Ian Dodkins; Anouska Mendzil; Leela O'Dea

### **Executive Summary**

Floating Treatment Wetlands (FTWs) have many benefits over Free Water Surface (FWS) wetlands:

1. Plant roots assisting in filtering and settling processes for sediment bound P and metals
2. Plant roots acting as a large surface area for micro-organism activity in: decomposition, nitrification, and denitrification (removal of BOD and N).
3. Mild acidification of water due to release of humic acids; and a C input from senescent vegetation, assisting denitrification.
4. They can adjust to varying water levels
5. A higher retention time is possible as they can be made deeper without submerging the vegetation

Percentage removal of nutrients and metals from effluent is around 20-40% higher in FTWs than in conventional FWS ponds. Removal efficiency, particularly of nitrogen, can be further increased with tighter control on the water chemistry (aeration; adding  $\text{CaCO}_3$ ; adding a carbon source). 20% coverage of islands is optimal for aerobic basins. 100% cover is optimal for anaerobic basins or aerobic basins where there is artificial aeration. The design the FTW and the control of basin water chemistry is essential for optimising treatment efficiencies. The passive use of activated carbon within layers of floating islands is unlikely to be cost effective.

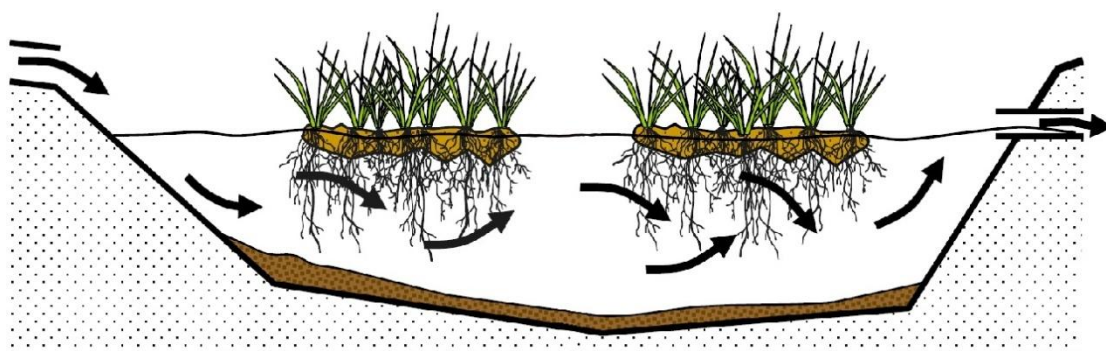


## Introduction

### Definition

Floating Treatment Wetlands (FTWs) comprise of wetland basins or cells, on which there are artificial mats containing emergent plants (Figure 1). This is not to be confused with treatment using floating leaved plants such as *Eichhornia crassipes* (Water Hyacinth), *Pistia stratiotes* (water lettuce), *Lemna* spp. (duck weed) or *Azolla* spp. (water fern) e.g. Reddy & Smith (1987); Kivaisi (2001), or where natural floating islands have established. Floating Treatment Wetlands are also referred to as Constructed Floating Wetlands (CFWs) or Floating Mat Constructed Wetlands, but we will use FTW throughout the review. Floating Islands (FIs) will be used to refer only to the islands within the treatment system. 'Effluent' refers to the water being treated at any stage within the wetland and 'inflow' refers to effluent entering the wetland, and 'outflow' as effluent leaving the wetland. Comparison will regularly be made between FTWs and other wetlands. Where 'conventional wetlands' is referred to, this means other treatment wetlands in general. Basins where there is open water but no islands, are known as Free Water Surface (FWS) wetlands.

The core of this review assesses process, performance and design of FTWs and includes a section on the potential for incorporating activated carbon into FTWs.



**Figure 1.** A Floating Treatment Wetland (FTW). Emergent plants are grown within a floating artificially constructed material. The roots are directly in contact with the effluent and can intercept suspended particles. The roots also provide a high surface area for microbiological activity. Image: Headley and Tanner (2006).

### 1.1 History

Floating islands are a natural occurrence, and can be found where emergent aquatic plants have broken from the land, sometimes developing in highly nutrient rich or sulphurous pools (Duzer, 2004). Floating leaved plants for treatment date back to the 11<sup>th</sup> Century, when the floating *Azolla* fern was used by Chinese and Vietnamese farmers to extract dissolved nutrients from wetlands and rice paddies, after which it was dried and applied as soil fertiliser (Whitton & Potts, 2002). The use of Water Hyacinth (*Eichhornia crassipes*) to remove nutrients also developed in South East Asia, and both have been used for centuries for water treatment within this region (Whitton & Potts, 2002). *E. crassipes* was suggested for use in the early 20<sup>th</sup> Century in both Auckland (Australia) and Yorkshire (UK) (Dymond, no date), and then in 1975 NASA used it to treat a sewage lagoon in the USA (Wolverton & McDonald, 1978).

Constructed floating islands were first developed in Japan in the 1990s, with *Cana generalis* being grown in floating beds to absorb nutrients from fish ponds and treatment basins (Wu

et al., 2000). Twenty percent coverage of soilless artificial floating islands, again using *C. generalis*, was later recommended to improve water quality in China (Bing & Chen, 2001).

Floating mats have also developed unintentionally in many open water treatment systems. Sometimes detrimental effects were observed, such as in Florida, where mats which had grown to 50% coverage moved with the wind across a shallow basin; scraping the bottom and disturbing sediments, resulting in increased outflow turbidity and phosphorus release (Kadlec & Wallace, 2009).

## 1.2 Range of applications

FTWs can be specifically designed or they can be installed in currently operating open water wetlands i.e. retrofitting. Potentially FTWs can be used with the same waste streams as conventional wetland systems. Some examples from the literature are:

### *Domestic wastewater treatment*

Conventional vegetated wetlands have often been advocated for wastewater polishing, rather than heavy nutrient loads, since they can become clogged and plants are very good at removing low concentrations of nutrients. However, given that there is primary sedimentation, FTWs can potentially deal with larger nutrient loadings since they have higher P and N removal capacity compared to conventional wetland treatment systems. The exposed roots aid sediment deposition, thus reducing turbidity, and there is greater surface area available for microbiologically mediated nitrification/denitrification reactions. Treatment with floating islands has been done on domestic waste in a highly controlled environment i.e. as a hydroponic system (Vaillant et al., 2003).

### *Metals treatment*

Wet detention ponds are used as a Best Management Practice for stormwater run-off in the USA (Chang et al., 2013). FTWs have thus become a popular choice as a retrofit for stormwater run-off treatment in these ponds (Chimney et al., 2006; Headley & Tanner, 2006; Tanner & Headley, 2008, 2011; Hwang & Lepage, 2011; Chang et al., 2012; Borne et al., 2013; White & Cousins, 2013; Winston et al., 2013). FIs are beneficial since they can treat water effectively even with the large fluctuations in water depth that occur during storms.

Strosnider & Nairn (2010) stated that FTWs are ideal for acid mine drainage, particularly if anaerobic conditions are maintained using high island cover. The resulting anaerobic conditions and the decomposing plant material aids denitrification, making the water more alkaline.

### *Agricultural waste*

The enhanced nitrate removal rate of FTWs makes them appealing in reducing pollution from agricultural run-off (Stewart et al., 2008; Yang et al., 2008) as well as for more concentrated wastewaters, such as from swine effluent (Hubbard et al., 2004).

### *Habitats*

FIs have sometimes been constructed specifically to create habitats e.g. to protect birds from land-based predators (Hancock, 2000), including a huge floating island of 3 700 m<sup>2</sup> in Sheepy lake (California) as a habitat for nesting Caspian Terns (Patterson, 2012). Only islands designed for effluent treatment will be covered in this review, however FIs do provide habitats as a secondary function. Emergent grasses can attract waterfowl and terrestrial birds because of the seeds, nesting material, nesting cover and available water. Fish have been introduced into some open water wetlands, however those that feed or nest on the

bottom have been found to disturb sediments, increasing suspended solids (Kadlec & Wallace, 2009, p.779).

Although usually not problematic, there have been incidences where large bird communities have contaminated open water treatment wetlands with faeces (Orosz-Coghlan et al., 2006), or have disturbed sediments, increasing turbidity (Knowlton et al., 2002). Geese herbivory can devastate the establishment of wetland plants, especially if planted during the spring or autumn migratory period (Kadlec & Wallace, 2009). However, a benefit of floating islands is that other herbivores e.g. rabbits, cannot usually access the islands. Mosquitoes may also be a problem with an open water system, particularly where monotypic vegetation such as cattail, bulrush and common reed restrict predator access (Knight et al., 2004). However, removing leaf litter, and ensuring that water depth is greater than 40cm (Sinclair et al., 2000) can reduce the problem.

#### *Tourism*

Treatment wetlands have been effectively marketed for tourism, especially those which provide good natural habitats for birds (Kadlec & Wallace, 2009). If the FTW is operated for tourism the design and operation is likely to have to include walkways, bird viewing areas and education centres. There may also be conflicting aims for depth regulation between habitat provision and treatment.

## **2. Processes**

FTWs, as with other wetland treatment systems, remove pollutants by four main processes (in order of importance): physical; biogeochemical; microbial and plants. These processes are similar in conventional wetlands, so much of the details provided here comes from that research. However, the larger surface area created by plant roots in FTWs tends to increase sedimentation (by filtering), microbiological decomposition, nitrification and denitrification, and also alter the water chemistry i.e. pH and dissolved oxygen (DO) concentrations. Processes will be discussed relative to the effluent constituents being removed.

### **2.1 Phosphorous removal**

Phosphorous within wetland effluents is usually as dissolved orthophosphate ( $\text{PO}_4^{3-}$ ), or organic phosphorus (Masters, 2012). The scarcity of P in natural environments results in efficient nutrient cycling within ecological systems (Kadlec & Wallace, 2009), thus there are few permanent routes for removal of P within treatment wetlands (Figure 1). The major mechanisms for P removal are accretion in peat/soil and soil adsorption.

#### *Settling and peat accretion*

Settling is the main process by which phosphorous bound sediments and BOD are removed from the water column (Kadlec & Wallace, 2009). Settling is a physical process whereby phosphate bound in particles sink to the bottom. Settling is increased in FTWs both by the roots (Masters, 2012) which filter the particles from the water column to later slough off to settle on the bottom, and by reducing currents and circulation caused by surface wind disturbance or water movements (e.g. from pumps) (Headley & Tanner, 2006; Chang et al., 2013). The reduction in movement is essential for preventing resuspension of sediment bound phosphorous into the water column, however, this reduction in currents also contributes to the risk that the basin will become anoxic (Van de Moortel et al., 2010). P retention within different conventional wetlands ranges from 40-60%, around 45 to 75 g/m<sup>2</sup>/yr (Vymazal, 2007), most of this being due to settling (and associated processes such as accretion and soil adsorption). P removal from FTWs is usually higher due to the additional filtering properties of the roots, reaching 81% (White & Cousins, 2013).

### *Soil adsorption*

Phosphorus is retained in the soils by binding to the soil surface. Soils with high clay content have high P adsorption capacity, which increases with lower pHs. Organic soils also adsorb P, with the adsorption capacity dependent on mineral components (Rhue & Harris, 1999). Al and Fe fix phosphorus in acidic soils, whilst Ca and Mg fix it in alkaline soils (Kadlec & Knight, 1996). This adsorption process is reversible, with an equilibrium between the bound P and the dissolved P in the soil porewater. The soil minerals and binding sites result in a 'phosphate buffering capacity' which determines where this equilibrium exists (Barrow, 1983). This has important implications for P removal, since reducing inflow P can cause P desorption from the sediments, actually producing a higher P outflow than inflow (Belmont et al., 2009).

### *Precipitation of P*

P adsorption occurs in aerobic waters, but as conditions become anoxic (reducing conditions) metals within the soil change valency, becoming soluble. This causes the release of phosphorus as a co-precipitate (precipitating due to the action of a true precipitate) from the soil (Kadlec & Wallace, 2009). In very low oxygen conditions, where the soils are anaerobic ( $E_h < -200$  mV) sulphate reduction occurs (Figure 4). This creates free sulphide which preferentially binds with Fe (as iron sulphide) preventing iron mineralisation of P. Thus, anaerobic conditions promote the release of P back into the water column (Kadlec & Wallace, 2009).

### *Plant uptake*

Plant uptake of P reaches only around 6% (Masters, 2012). If a FTW has a P removal up to 81% (White & Cousins, 2013), this means around 75% is removed predominantly by settling or storage in other sinks. Much of the P in plant uptake is also difficult to remove permanently from the system by harvesting because it is stored in the roots, or it re-enters the system as litter (see Section 2.8 Harvesting). Vymazal (2007) considers that harvesting of conventional wetlands is only useful in low P effluents (e.g. polishing) with around 10-20 g P/m<sup>2</sup>/yr, where uptake is not limited by growth rate. FTWs may be able to absorb more P, due to their roots being suspended directly in the effluent, and plant roots are more accessible for harvesting, but dredging is still likely to be the most effective method of permanent removal.

### *Microbial and Algal uptake*

Bacteria and algae are important in P cycling within the soils, rhizosphere and water column (Vymazal, 2007). P uptake by microbes in conventional wetlands is very fast, but they store very little (Vymazal, 2007). Thus, having higher surface area and consequently higher microbial mass, microbes in a FTW are likely to be a larger sink of P than in conventional treatment wetlands, however nutrient cycling is likely to result in little net removal, except through sedimentation of dead organic microbial matter.

### *Fish Uptake*

In South East Asia it is common to use fish for nutrient recovery in ponds receiving human effluent (Cairncross & Feachem, 1993). Fish eat periphyton (such as algae, cyanobacteria, heterotrophic microbes, and detritus) (Azim et al., 2005) as well as fungi, protozoa, phytoplankton, zooplankton, invertebrates and invertebrate larvae, and some species are piscivorous. In treatment wetlands fish are usually chosen for their adaptation to low oxygen levels, for example *Gambusia affinis* (mosquito fish) in warm temperate to tropical conditions, and *Notropis fundulus* (black-striped top minnow) or *Umbra limi* (central mudminnow) in temperate climates with over 77 different fish species being used in North American treatment wetlands (Kadlec & Wallace, 2009). Sometimes *Oreochromis* spp.

(Tilapia) and Bass have colonised previously unpopulated treatment wetlands (Kadlec & Wallace, 2009).

Li & Li (2009) examined nutrient removal from aquaculture effluent using floating islands (17% cover) planted with the aquatic vegetable *Ipomoea aquatic*. There was artificial aeration and it was populated with *Aristichthys nobilis* (silver carp), *Siniperca chuatsi* (mandarin fish; carnivorous) and *Carassius auratus gibelio* (crucian carp). Around 34% of TN and 18% of TP was removed from the system, and of this around a third (34%) of removed TP and TN was removed by fish. This was around the same that was removed by sedimentation.

Kania (2014, unpublished) suggests that FTW facilitate the sustainable growth of fish and demonstrates that FTW significantly increase fish biomass that can be harvested from the waterway. Fish harvesting enables P removal from the effluent with fish being made into meal which can be used for pork or poultry farming or in pet food. There must be no toxins or toxic metal contaminants in the effluent, especially contaminants that may bioaccumulate. Also, if it is to be sold for human consumption the fish need to be cooked well since there is the potential for contamination by pathogens, particularly the tapeworm *Clonorchis sinensis* (Cairncross & Feachem, 1993).

Fish can disturb bottom sediments, releasing P, particularly those that feed or nest on the bottom e.g. *Cyprinus carpio* (Carp) (Kadlec & Wallace, 2009, p.696).

#### *Problems with phosphorous removal*

Generally, wetland treatment only produces temporary storage of P, in contrast to N and C which can be released as gases through microbiological degradation ( $N_2$  and  $CO_2$ ). Indeed, Yousefi and Mohseni-Bandpei (2010) stated that P can be considered as a conserved entity. Most P is stored in sinks such as sediments (95%; Masters, 2010), plants, microbes and algae, but this P is recycled. These sinks give an initial period of apparent P removal. However, once the wetland is established, nutrient cycling results in similar outflow P levels to inflow. Even regular harvesting of plants only removes around 6% (Masters, 2012) of P inflow, if both the roots and shoots are harvested. Thus, Kavanagh & Keller (2007) concluded that at least 90% of P eventually passes through a wetland system and is released in the effluent.

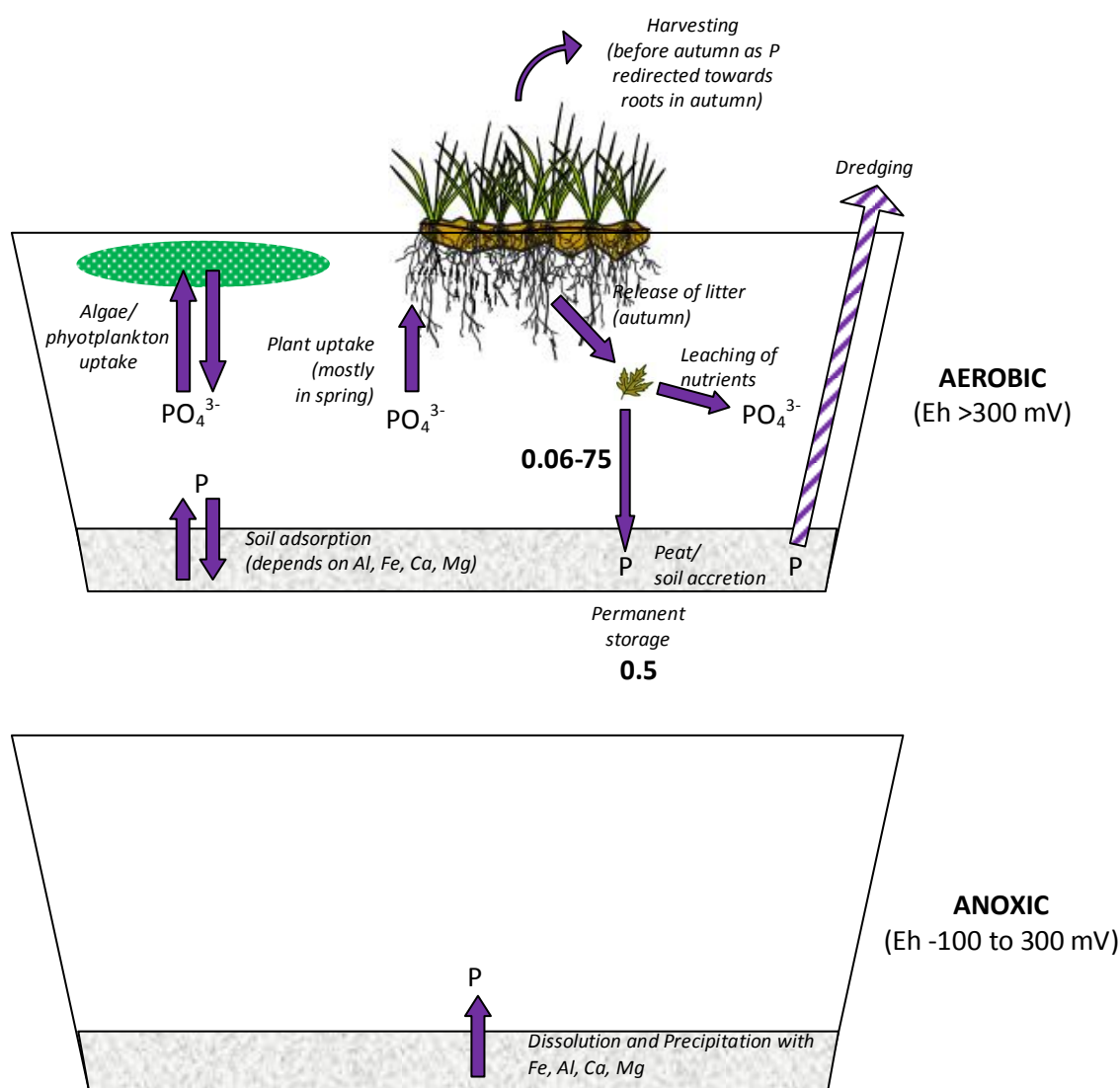
Some wetland treatment systems can even export more P than they receive, such as a stormwater wetland in North Carolina which had median removal efficiencies of – 95% to 70%; at times exporting twice as much P as it was receiving (Line et al., 2008). This can occur both due to physical disturbance of the sediments releasing P, the re-release of P from biodegradation of organics (Sundaravadivel & Vigneswaran, 2001), or anoxia which can also result in the sudden release of P as a co-precipitate (Maine et al., 2005).

Sudden P releases into the water column can potentially have other detrimental effects. Since P is usually the limiting factor for biological activity in freshwaters (Schindler et al., 2008), a large P release can result in nitrogen becoming limiting. This promotes the growth of Cyanobacteria blooms which as well as producing harmful toxins, also extract N from the atmosphere (Conley et al., 2009).

Masters (2012) is thus emphatic that dredging is important for long term removal of phosphorus from a FTW. Kadlec and Wallace (2009) detail projected working life of different types of wetlands with different soils, ranging from around 10 to 170 years, but dredging around every 10 years (Masters, 2010) would be ideal for sustained P removal with most effluents.

A minor route of P removal is phosphine ( $\text{PH}_3$ ). It is usually found in very low amounts (e.g.  $47 \text{ ng/m}^3$  of water in marshes), mostly bound to sediments but with around 10% of this dissolved in the water (Hana et al., 2010). However, it can be released from highly anaerobic wetlands ( $\text{Eh} < -200 \text{ mV}$ ) (Gassmann & Glindemann, 1993) as phosphine gas. Devai and Delaune (1995) calculated a gaseous release rate of  $1.7 \text{ g P/m}^2/\text{yr}$  from a bulrush wetland treatment system.

Thus, treatment wetlands have various sinks (algae, plants, microbes, soils) which vary in their capacity to absorb P from the effluent based on conditions such as available surface area, soil type, pH and redox potential. FTWs limit the resuspension of particulates since the islands reduce water movement within the wetland and the roots filter out particulates (Borne et al., 2013), thus increasing P sedimentation. However, dredging is essential to long term functioning of a FTW for P removal, and regular harvesting can be useful at low P loadings (Figure 1).



**Figure 2. Summary of phosphorus processes in aerobic and anoxic wetlands.**

Soil/peat accretion and soil adsorption is the major process and major (95%) sink. However, sorption of P into the soil is reversible. Without harvesting or dredging P removal eventually stops. Numbers in **bold** are  $\text{g P/m}^2/\text{yr}$  that may be removed or added during the processes; *italics* indicate the name of the process, with specific conditions required in brackets.

## 2.2 Nitrogen removal

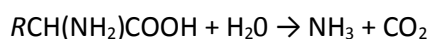
Nitrogen is the principal target for treatment in many wetlands. Effluents contain organic nitrogen compounds, which break down principally to ammonia, from which nitrite and nitrate can form through a microbiological nitrification process. Different micro-organisms within anoxic zones can denitrify this nitrate to permanently release N<sub>2</sub> gas from the basin. Agricultural wastes may already have high concentrations of nitrate nitrogen as they enter the wetland. Conversion between different forms of N depends on many factors, including DO, available carbon and pH.

### 2.2.1 Nitrogen removal in aerobic water

#### *Ammonification (mineralisation)*

Dead and decaying organic material is broken down into ammonia by microbes, either utilising the energy released or absorbing the ammonia for use as microbial biomass. Ammonification increases with temperature, being optimal at 40-60 °C, and with organic compound availability (especially when they have low C/N ratios) (Reddy & Patrick, 1984). Optimum pH is between 6.5 and 8.5 (Vymazal, 2007). Ammonification usually takes place under aerobic conditions (oxidative deamination).

**Equation 1:** Break down of organic N (example with amino acid) to ammonia

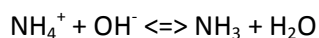


Ammonification rates can vary greatly e.g. between 0.004 and 0.53 g N/m<sup>2</sup>/d (Reddy & D'Angelo, 1997; Tanner et al., 2002). The root zone of a FTW is likely to be a good location for ammonification.

#### *Ammonia volatilisation*

Ammonia exists in an equilibrium between its dissolved ammonium form (NH<sub>4</sub><sup>+</sup>) and its gaseous form (NH<sub>3</sub>); Equation 2. Below pH 8.0 ammonia loss as gas is negligible (Reddy & Patrick, 1984). At a pH around 9.3 losses due to volatilisation can become significant (Vymazal, 2007). N removal rates due to ammonia volatilisation have been measured at 2.2 g N/m<sup>2</sup>/d in wetlands (Stowell et al., 1981).

**Equation 2:** Conversion of dissolved ammonium to ammonia gas



Algal photosynthesis often elevates pH values during the day (Vymazal, 2007), thus increasing ammonia volatilisation. However, FTWs may inhibit this due to (i) islands shading algae and reducing the area of the air-water interface, and (ii) plants releasing humic acid, which reduces the pH (Van de Moortel et al., 2010).

#### *Nitrification*

Within aerobic water micro-organisms convert ammonium to nitrate in a process called nitrification. Directly adjacent to plant roots there is an aerobic zone (Reddy et al., 1989), which means that FTW are likely to have elevated denitrification rates due to the availability of root surface area.

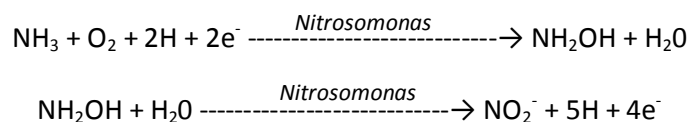
Kadlec & Wallace (2009; p.280) note that nitrification in wetlands is quite different from nitrification in conventional Waste Water Treatment Works (WWTWs). Whilst nitrification is



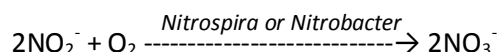
commonly considered a two step process in conventional WWTWs, in natural wetlands it is now believed to have three stages (Bothe et al., 2000); Equation 3.

**Equation 3:** The three stage nitrification process, converting ammonium to nitrite, then nitrate.

Nitrification (2 stages)



Nitrification (1 stage)



Due to the different processes less oxygen and alkalinity is consumed in wetlands during nitrification than in conventional WWTWs (Kadlec & Wallace, 2009). *Nitrospira* is also much more prominent as a nitrifier than *Nitrobacter* in wetlands (Austin et al., 2003).

Nitrification is influenced by temperature (optimum 25-35 °C), pH (optimum 6.6-8), alkalinity, microbial populations present, DO and ammonium concentrations (Vymazal, 1995). Below 4 °C nitrifying bacteria *Nitrosomonas* and *Nitrobacter* do not grow (Paul & Clark, 1996). Kadlec & Wallace (2009; p.280) note, unlike WWTWs, there is little evidence that a low C/N ratio in wetland effluents improves nitrification rates.

In wetlands, for every g of ammonium oxidised to nitrate 2.28 g of oxygen and 7.1 g of alkalinity as calcium carbonate are consumed (Kadlec & Wallace, 2009; p.279) i.e. nitrification requires aerobic conditions and will consume alkalinity and oxygen, becoming increasingly acidic and anaerobic. Wetlands have nitrification rates of 0.01 to 2.15 g N/m<sup>2</sup>/d (mean of 0.048) (Reddy & D'Angelo, 1997; Tanner et al., 2002), though this may be much higher for FTWs due to the large root surface area within the aerobic zone.

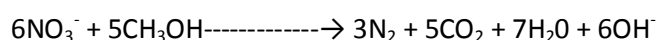
Low oxygen conditions can result in nitrite (NO<sub>2</sub><sup>-</sup>) being produced instead of completing the process toward nitrate (Bernet et al., 2001). The consequence of this is that in a later denitrification stage, some of the nitrite is converted into nitrous oxide (N<sub>2</sub>O), a potent greenhouse gas. Sufficient oxygenation in nitrification basins is therefore recommended.

### 2.2.1 Nitrogen removal in anoxic water

#### Denitrification

Denitrification is the microbiologically mediated conversion of nitrate into nitrogen gas, which is then released from the wetland into the atmosphere. A carbon source is required for denitrification. The equation can be written in many ways, depending on the source assumed (Equation 4).

**Equation 4:** Denitrification of methanol, producing nitrogen gas and alkalinity



In many ways denitrification is the converse of nitrification, making the water more alkaline and requiring anoxic or anaerobic conditions. Microorganisms denitrify because in the absence of dissolved oxygen for reduction, they reduce nitrate. Although methanol is used



for illustration here as a source of carbon, usually it is large organic molecules. It is calculated that per g of  $\text{NO}_3^-$  around 3.02 g of organic matter (or 2.3g of BOD) is consumed, and around 3g of alkalinity as  $\text{CaCO}_3$  is produced (Kadlec & Wallace, 2009).

The optimum pH is 6 to 8 (Paul & Clark, 1996) being negligible below pH4 (Vymazal, 2007). Denitrification is very slow below 5 °C, but increases with temperature up to 60 or 75 °C, then decrease rapidly (Paul & Clark, 1996). More nitrate can speed up the process, but the limiting factor in denitrification is often the carbon supply (Kadlec & Wallace, 2009), especially if BOD has settled out in previous treatment basins. A C/N ratio of 5:1 is suggested to ensure carbon does not become limiting (Baker, 1998) although this may be an overestimate if much of the C is labile (Kadlec & Wallace, 2009). Lower pHs can assist with breaking down lignin in cell walls, increasing the litter quality for denitrification processes (Ding et al., 2012).

Often an anaerobic denitrification basin is placed after an aerobic nitrification basin. This enables all the ammonium to be converted to nitrate prior to denitrification, thus maximising total N removal. However, even in a well oxygenated basin there are areas of low mixing, and deeper waters and sediments, where oxygen levels are low enough to produce denitrification (Figure 3, Figure 4), and in anoxic basins nitrification can occur on the surface of roots where the plants have transported oxygen (Kadlec & Wallace, 2009, p.281). Thus both nitrification and denitrification processes can be achieved within a single basin, though controlling the treatment efficiency may be more difficult.

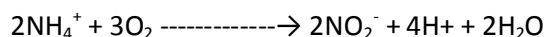
Floating islands can aid denitrification by producing anoxic conditions through the restriction of oxygen diffusion into the water column. Also, roots and plant litter, as well as coconut coir on islands (Baquerizo et al., 2002), can act as sorption sites, with biofilms developing which increase denitrification rates and thus  $\text{NO}_3^-$  removal rates (Vymazal, 2007). Denitrification releases are about 0.003 to 1.02 g N/m<sup>2</sup>/d in wetlands (Vymazal, 2007), though this could be higher in FTWs due to more biofilm area and more sorption sites.

#### *Anaerobic Ammonia Oxidation (ANAMMOX)*

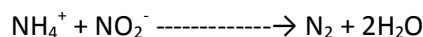
The bacteria involved in this process were only discovered in 1999. *Planctomycetes Nitrosomonas eutropha* utilises ammonium ions and nitrite (from nitrification of ammonium) to produce nitrogen gas. This can be represented as in Equation 5.

**Equation 5.** The ANAMMOX process

Formation of nitrite



ANAMMOX

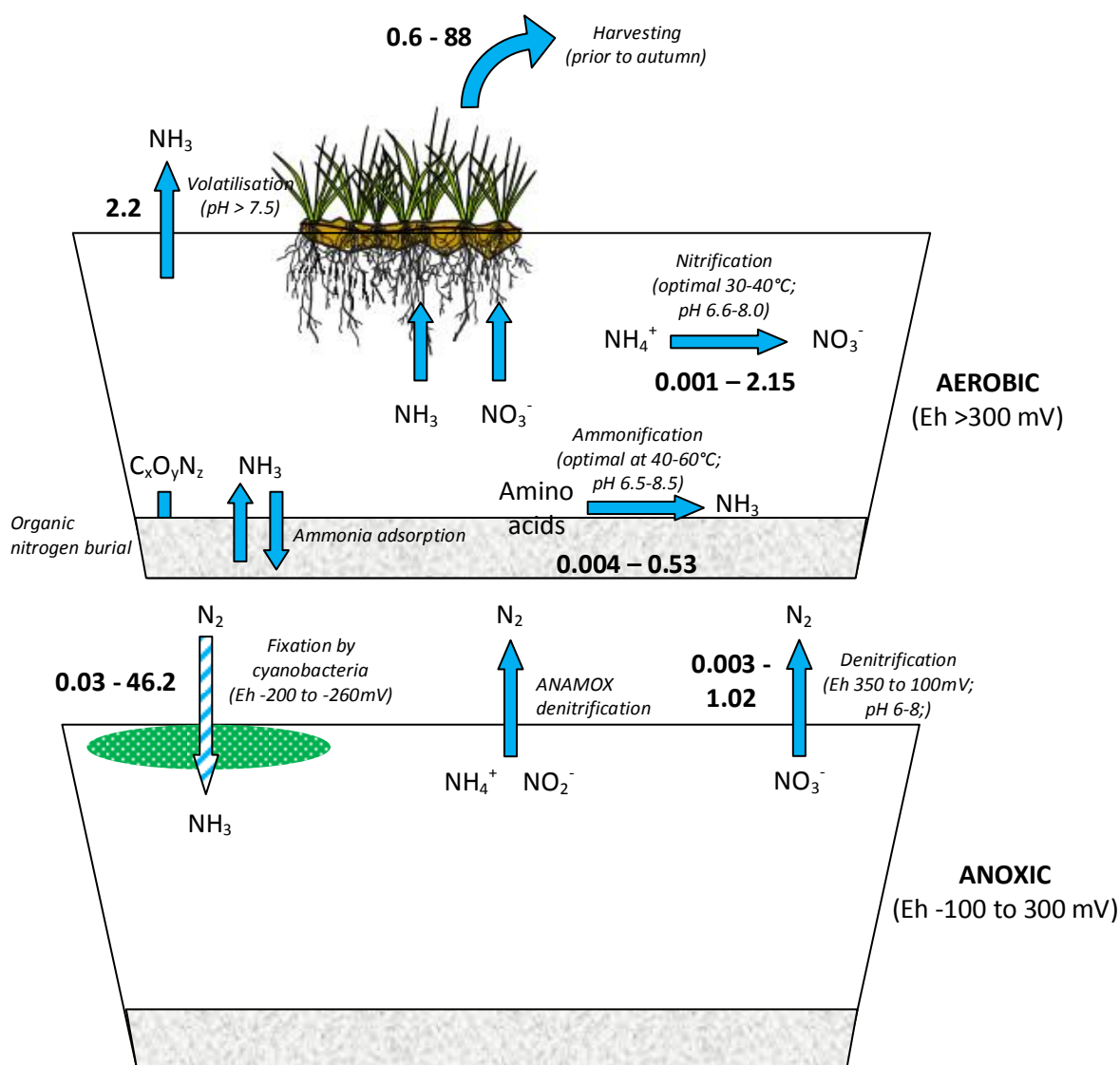


This denitrification process uses less than half the oxygen (1.94g O per gram of  $\text{NH}_4^+$ ) of the standard denitrification process, and requires no carbon substrate (Kadlec & Wallace, 2009). ANAMMOX processes occur in many types of wetlands when there is severely restricted oxygen. Bishay & Kadlec (2005) found that in a Free Water Surface wetlands there were more ammonia losses than could be accounted for by the oxygen consumed under normal denitrification. There was also a lot of nitrite present in this wetland, and very little carbon, suggesting that these conditions were conducive to the ANAMMOX reaction.

### Plant uptake

Nitrogen uptake by plants in conventional wetland treatment is low (up to 6-8%) compared to microbial denitrification (up to 61-63%) (Metheson et al., 2002). Vymazal (2007) estimates that for conventional wetland systems plant harvesting is useful for N removal if loading is only around 100-200 g N/m<sup>2</sup>/yr. If N removal is a priority, designing and operating the basins to maximise nitrification/denitrification by microorganisms is probably more cost effective.

N is predominantly taken up by plants in the form of ammonia, but also as nitrate. Much of this is returned to the system when tissues senesce (Kadlec & Wallace, 2009).



**Figure 2.** Summary of nitrogen processes in aerobic and anoxic wetlands. Primary settlement of effluent is assumed prior to entering the wetland. Numbers in **bold** are g N/m<sup>2</sup>/yr that may be removed or added during the process; *italics* indicates the process, with specific conditions required in brackets. The striped blue arrow indicates nitrogen fixation that would not normally occur unless the anoxic pond becomes anaerobic (Eh < -200 mV). Permanent removal of N is only through ammonia volatilisation (minor), denitrification (including ANAMOX) and harvesting. Organic nitrogen burial (associated with litter) and ammonia adsorption (associated with clay soils) are relatively minor processes.

### Problems with nitrogen removal

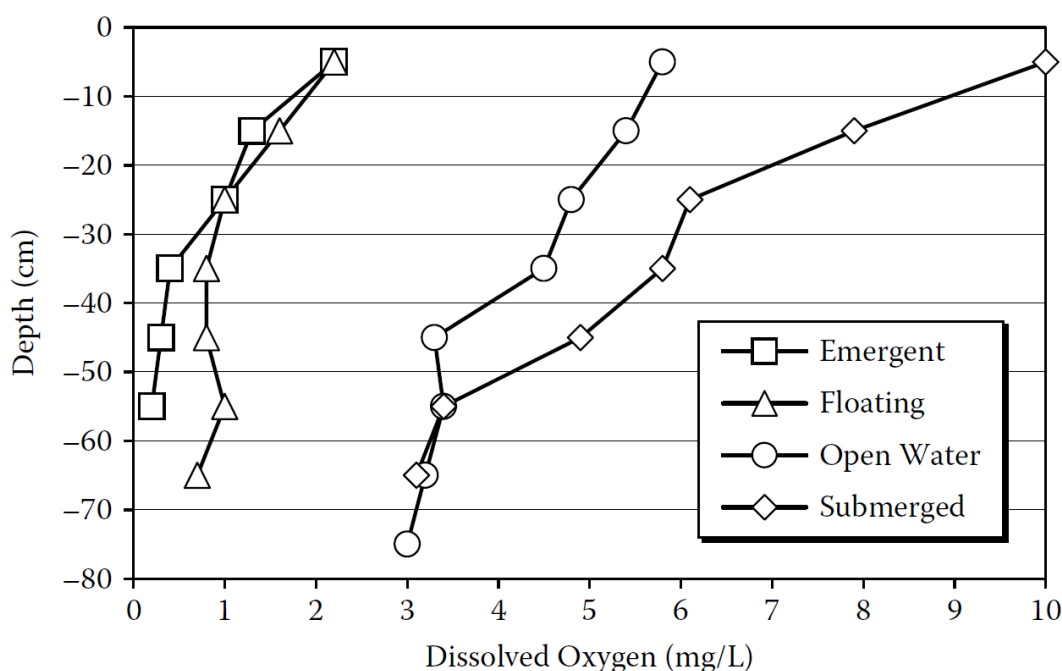
NH<sub>4</sub> removal rates in conventional wetlands vary between 35 and 50% in Europe (Verhoeven & Meuleman, 1999; Vymazal, 2002). FTWs have shown removal rates from -45% to 75% for NH<sub>4</sub> and between 36% and 40% for total nitrogen (Boutwell, 2002; DeBusk & Hunt, 2005; Gonzalez et al., 2005).

Problems with nitrogen removal are associated with producing the correct microbiological conditions; aerobic for nitrification and anoxic for denitrification, as well as ensuring sufficient carbon supply for the later. These are discussed in the design section.

## 2.3 Oxygen

### Factors influencing oxygen concentrations

Wetlands typically have slow flow, incomplete mixing, and rapidly decreasing oxygen profiles with depth (Figure 3). Anoxic zones develop just below the substrate in shallower basins and also in the lower regions of the water column in deeper basins (Kadlec & Wallace, 2009). Oxygen can be rapidly depleted in wetlands due to microbiological activity, particularly with nitrification and decomposition (Kadlec & Knight, 1996). FTWs exacerbate oxygen depletion both due to high rates of microbiological activity (nitrification) and due to the islands restricting diffusion of oxygen back in to the water i.e. reducing air-water contact area and reducing wind disturbance (Van de Moortel et al., 2010). This makes FTWs particularly susceptible to unwanted drops in DO, especially at high percentage cover of islands.



**Figure 3.** Vertical profiles of dissolved oxygen in various types of FWS (Free Water Surface) wetlands, Florida. Data from 141 profiles collected over a 2½ year period. Data from Chimney et al. (2006), Figure from Kadlec & Wallace (2009). FTWs are most readily compared to floating plant systems.

### Temperature affects

Oxygen saturation of water varies with temperature: at 25 °C dissolved oxygen is 8.2 mg/l, and at 5 °C it is 12.8 mg/l. However Kadlec and Wallace (2009) note that the poor mixing of waters limits the dissolution of oxygen such that reaeration is very slow, even in open

wetlands. They estimate that it takes 2 to 4 days to reaerate an open wetland basin from 0 to 90% DO, with typical winds. This is likely to be even slower in FTWs.

### Plants

Submerged photosynthesising plants and algae release in the range of 0.26 and 0.96 g/m<sup>2</sup>/d of O<sub>2</sub> during photosynthesis (Kadlec & Wallace, 2009, p138), oxygenating the water.

Emergent plants bring O<sub>2</sub> to the roots, but O<sub>2</sub> delivery usually matches respiration requirements, so there is little net input into the water column (Brix & Schierup, 1990). Studies by Tanner and Headley (2011) and White and Cousins (2013) both found a high level of oxygen depletion in basins due to floating islands.

Tanner and Headley (2011) not only illustrated how oxygen depletion is higher in FTWs, but also that oxygen depletion is higher when there are plants rather than mats with artificial roots (sisal) (Table 1). This oxygen depletion is likely due to the higher rate of microbiological activity associated with plant roots. Although the relationship between oxygen depletion and root biomass was weak, there was little oxygen depletion due to the floating mat alone and even the mat with artificial roots.

**Table 1.** Oxygen depletion (%DO) at subsurface and bottom of mesocosms after 7 days due to the effect of Floating Islands, ordered from highest to lowest. Influent DO was 95%, floating island coverage was 50%. Root biomass (dry weight) also shown. Adapted from Tanner and Headley (2011).

	subsurface DO (%)	bottom DO (%)	Root biomass (g/m <sup>2</sup> )
Control (no floating mat, but equivalent shading)	87	85	
Floating mat only	85	84	
Mat + soil + artificial roots	85	84	
Mat + soil media	80	79	
Mat + soil + <i>Juncus edgariae</i>	68	66	299
Mat + soil + <i>Schoenoplectus tabernaemontani</i>	68	67	184
Mat + soil + <i>Carex virgata</i>	58	57	533
Mat + soil + <i>Cyperus ustulatus</i>	50	48	329

Van de Moortel et al. (2010) found redox potentials to be decreased due to floating islands: at both 5cm and 60cm depths the FTW has much lower O<sub>2</sub> than an open water basin: at 5cm redox is 68 (open water) cf. -25 (FTW); at 60cm redox is: -93 (open water) cf. -122 (FTW). They did claim that roots can aerate island matting. However, there was little difference between the mat redox potential (72 mV ± 478) and the redox potential 5cm below the surface of an open water basin at (68 mV ± 225).

A liability with FTWs is that during summer periods, due to high rates of microbiological activity and insufficient O<sub>2</sub> exchange with the atmosphere, the basin can become anaerobic, causing sulphide toxicity which then kills the plant roots (Lamers et al., 2002) and consequently reducing the effectiveness of treatment. Reduction in treatment efficiency due to anoxia was found in several studies, but usually when the floating islands occupied 50% or more of the surface water area (Van de Moortel et al., 2010; Borne et al., 2013).

## 2.4 Redox potential

Oxidation is the loss of electrons during a reaction. This is usually through a substance combining with oxygen, as it is energetically the most favourable oxidant. Redox potential is the tendency of a system to oxidise substances i.e. in high redox potential water, incoming organic substances will be rapidly oxidised (an oxidising environment) whereas in low redox potential waters substances will be reduced (a reducing environment). An example of reduction would be where hydrogen combines with carbon to produce methane.

Redox potential is strongly associated with the oxygenation of the water, but it is not identical, since substances other than  $O_2$  can oxidise. Zonation usually occurs in a wetland with oxygen being the oxidiser near the surface, then as DO decreases other substances become oxidisers, with reactions releasing less energy with successively weaker oxidisers. This is in the order  $O_2$ ,  $NO_3^-$ ,  $MnO_2$ ,  $FeOOH$ ,  $SO_4^{2-}$  then  $CO_2$ .

The decline in free oxygen reflects the redox potential (Eh), also known as the oxidation-reduction potential (ORP), of the water i.e. the tendency of a chemical to acquire electrons, measured as electric potential (mV). At  $Eh > 300mV$  (measured with a platinum electrode) conditions are considered aerobic, at  $< -100 mV$  conditions are anaerobic, and between these (near-zero Dissolved Oxygen) conditions are anoxic (Figure 4).

Redox Potential	Reactions		Zone
$> +300 mV$	Oxygen reduction	I	Aerobic
---			
$+ 100 \text{ to } +300 mV$	$NO_3^-$ and $Mn_4^+$ reduction	II	Anoxic
$+100 \text{ to } -100 mV$	$Fe_3^+$ and $Mn_3^+$ reduction	III	
$-100 \text{ to } -200 mV$	$SO_4^{2-}$ reduction	IV	Anaerobic
$< -200 mV$	$CH_4$ formation	V	

**Figure 4.** Redox zonation in wetlands, based on Kadlec & Wallace (2009). This vertical zonation can be found in deep lentic environments, particularly where there is high oxygen consumption e.g. by microorganisms.

At high redox potential phosphorus can form insoluble complexes with oxidised iron, calcium and aluminium. Organic compounds which comprise most of the BOD are oxidised using oxygen by bacteria, releasing carbon dioxide. At lower redox potentials organic material does not decay quickly. The water is anoxic, with reducing conditions predominating. Manganese and iron are both reduced (Equation 6)

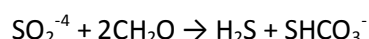
**Equation 6.** Reduction of manganese and iron in anaerobic conditions



This reduction causes metals to precipitate out of the sediments back into the water column, bringing P with them, as a co-precipitate (Van de Moortel et al., 2010).

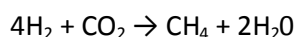
Further decreases in oxygen (below -100mV) result in anaerobic conditions, whereby sulphate is reduced to hydrogen sulphide, which although soluble, can be released as gas at low pH (Kadlec & Wallace, 2009). Usually this reduction is undesirable in wetlands, except in acid mine treatment.

**Equation 7.** Reduction of sulphate to hydrogen sulphide



Eventually, at very low redox potential (below -200mV)  $\text{CO}_2$ , formate, or acetate, is reduced to methane ( $\text{CH}_4$ ) by bacteria.

**Equation 8.** Reduction of carbon dioxide to methane.



## 2.5 BOD, Suspended Solids and Carbon

### *Biological Oxygen Demand*

Biological Oxygen Demand (BOD) is a measure of oxygen consumption by microorganisms due to the oxidation of organic matter; usually measured in the lab over 5 days ( $\text{BOD}_5$ ). BOD of inflows are typically high, unless the treatment basin is being used just for polishing previously treated wastes. BOD decreases rapidly (around 50% decrease within 6 hours) as it passes through a wetland due to decomposition and settling of organic carbon, finally reaching a non-zero plateau (Kadlec & Wallace, 2009). Even if the waters are not aerobic, fermentation and sulphate reduction can remove carbon from the system.

### *Carbon*

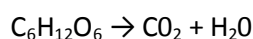
Most carbon entering a wetland is organic. Microbiological processes are the main method for removing carbon, through the oxidation of organic compounds, releasing energy. In aerobic waters, respiration takes place (Equation 9), releasing  $\text{CO}_2$  to the atmosphere. In anaerobic zones there are four main processes which can take place: (i) fermentation producing either lactic acid or ethanol (ii) methanogenesis producing gaseous methane (iii) sulphate ( $\text{SO}_4^{2-}$ ) reduction producing carbon dioxide and hydrogen sulphide, and (iv) denitrification, producing carbon dioxide and gaseous nitrogen.

Settling is also an important removal method (although the carbon is retained in the sediments). In FTWs plants have been shown to remove around  $5.9 \text{ g BOD/m}^2/\text{day}$ . The large surface area provided by roots can produce a higher rate of microbial decomposition (Brisson & Chazarenc, 2009), but roots also physically entrap particulates onto the biofilm which then fall in clumps and settle out, providing a significant removal pathway for suspended solids (Smith & Kalin, 2000; Headley & Tanner, 2006; Van de Moortel et al., 2010; Borne et al., 2013). Settling is further encouraged by flow resistance through the roots and flow reduction caused by wind shielding of the surface. Particulate carbon, and carbon

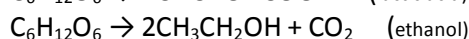
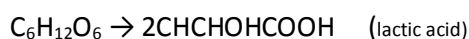
bound in litter, if it is not decomposed, accumulates in the sediments, particularly where conditions are anaerobic (Kadlec & Wallace, 2009).

**Equation 9.** Microbiological decomposition of organic compounds.

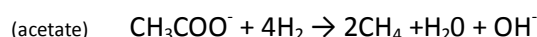
Respiration



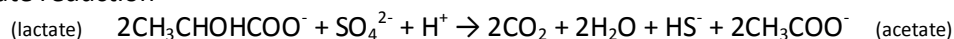
Fermentation



Methanogenesis



Sulphate reduction



Denitrification

(see Equation 4)

Unlike submerged plants, which obtain carbon from the water, carbon uptake by emergent plants is from atmospheric  $\text{CO}_2$ . Plants thus bring carbon into the system through photosynthesis and the deposition of organic matter. However, the net effect of plants in wetlands is to reduce BOD due to plant respiration, increased settling, and increased decomposition processes (Masters, 2012). Also, where there is carbon limitation in anoxic or anaerobic basins, the C provided by the deposition of litter can be important in increasing denitrification rates (see Section 2.2.1).

Settling of BOD is also affected by basin depth, residence time and water movement (Kadlec & Wallace, 2009). Theoretically higher temperatures should increase microbial decomposition rates. Bacteria have limited activity below  $5^\circ\text{C}$ , but in conventional wetlands there is no significant temperature dependence above this (Akratos & Tsihrintzis, 2007; Kadlec & Wallace, 2009). This may be due to limitations in oxygen transfer rates or restricting factors in one or more of the many C processes (Kadlec & Wallace, 2009).

In anoxic (reducing) conditions, the presence of sulphate contributes to the removal of organic matter (BOD/COD) by acting as a coagulant and thus increasing settling rates (Huang 2005).

## 2.6 Metal removal

Metal removal from wetlands is predominantly through forming complexes with organic matter, and through being coated in iron or manganese oxyhydroxides (Kadlec & Wallace, 2009). This either occurs in the sediments, or they settle out into the sediments. Under anoxic conditions Cu, Zn, Pb, Ni and Ca form insoluble metal sulphides which will settle out. Even in aerobic basins, decomposition of organic matter usually means there is an anoxic layer just below the surface oxic layer ( $\approx 1\text{cm}$ ) in which these metal sulphides can form.

Predicting metal removal from wetlands can be very difficult, depending on the structure of the sediments and many factors of the water chemistry, with models regularly being wrong by orders of magnitude (Kadlec & Wallace, 2009). Factors that affect metal removal include the Cation Exchange Capacity (CEC) of the sediments, pH (circumneutral usually being optimum), redox potential, the availability of sulphur for the formation of metal sulphides, and the formation of iron and manganese oxyhydroxides (which allow co-precipitation) (Kadlec & Wallace, 2009). Organic soils with humic acids and phenolics increase the CEC and thus adsorption of metals. Sedimentation of metals can result in long term storage, depending on the availability of organics with which metals can complex, although metal accumulation can eventually saturate the soil sink and result in biological toxicity (Kadlec & Wallace, 2009). Thus (careful) dredging is required in the long term to permanently remove metals and ensure the wetland continues to operate effectively.

Uptake by plants is much less important than that by sedimentation, and where metals are taken up, they are mostly stored in the roots. Table 2 shows percentage removal of metals by plants in a conventional wetland and how this is allocated in the roots and shoots.

**Table 2.** Percentage removal of metals by plants in a conventional treatment wetland and how this is allocated to the roots and shoots (adapted from Nolte and Associates, 1998).

<b>Metal</b>	<b>Roots (%)</b>	<b>Shoots (%)</b>	<b>Total (%)</b>
Ag	2.0	0.0	2.0
As	10.1	0.6	10.7
Cd	13.3	0.0	13.3
Cr	16.8	2.2	19.0
Cu	5.5	0.6	6.1
Hg	6.7	0.0	6.7
Ni	4.7	0.3	5.0
Pb	11.8	2.0	13.8
Zn	6.1	0.4	6.5

Despite plant uptake being low, FTWs have been shown to greatly increase metal removal compared to unvegetated retention ponds. For example Borne et al. (2013) compared treatment in a normal stormwater retention pond with one retrofitted with a floating island. With concentrations of 0.0092 mg Cu/l and 0.035 mg Zn/l in the inflow, particulate Cu and Zn removal was 19% and 40% (respectively) in the normal pond, and 50% and 65% with a floating island. Tanner & Headley (2011) found the removal of dissolved Cu and Zn to be 5% and 1% without a floating island, and 50% and 47% with an island. These authors believe that the benefit of the floating island wasn't principally due to plant uptake. Indeed, Tanner & Headley (2011) found mean plant uptake rates were 0.059-0.114 mg Cu/m<sup>2</sup>/d and 1.2-3.3 mg Zn/m<sup>2</sup>/d, accounting for less than 4% of Cu removal and less than 10% of Zn removal. This was a mesocosm experiment without bottom sediments and with predominantly dissolved metals, so values of plant uptake were probably higher than they would be in a normal FTW.

Tanner & Headley (2011) and Borne et al. (2013) considered that the improved performance with floating islands was due mainly to: (i) interception by the plant roots, (ii) humic acid release from the plants, which reduced alkaline waters to circumneutral pH (Van de Moortel et al., 2010), improving metal complexation and therefore flocculation and settling (Mucha et al., 2008) and (iii) The islands reducing the redox potential to the extent that insoluble metal sulphides formed.



The exact mechanisms of metal removal depend on the specific metal. Most zinc within effluents is in particulate form and is removed predominantly through settling, sorption to organic sediments and chemical precipitation/co-precipitation (Kadlec & Wallace, 2009). It can form precipitates with sulphur (ZnS) and carbonate from the water (ZnCO<sub>3</sub>) and it co-precipitates with Fe, Mn, Al oxyhydroxides. However, ZnS does not readily precipitate in neutral waters (Younger, 2000), only in more alkaline waters (>7.5). Also, for co-precipitation, the other metals must be present in the effluent, and even then, Fe and Mn oxides are not stable in anoxic waters (Knox et al., 2004). Warmer water temperatures are also correlated with Zn removal, probably due to increased sorption rates (Borne et al., 2013). Aerobic wetlands are expected to absorb about 0.04g Zn/m<sup>2</sup>/d (PIRAMID consortium, 2003). Similar to Zn, Cu removal rates increase with temperature, however adsorption is better at more neutral pH (Borne et al., 2013). They also concluded that reduced oxygen resulted in a high production of Cu sulphide precipitates in basins with floating islands.

High loadings of effluent and insufficient adsorption capacity or saturation of the potential sinks (organic carbon, metal hydroxides, high CEC soils) can result in decreasing treatment capacity as well as increasing toxicity. Toxicity can be a biological problem, particularly in open water treatment systems where birds, amphibians and freshwater invertebrates have direct access to the basin (as opposed to subsurface flow systems) (Kadlec & Wallace, 2009). Sorption capacity in studies listed by Kadlec and Wallace estimate between 20 and 780 years operation of a wetland with metal loading. Careful dredging (avoiding resuspension) can be applied to remove contaminated sludges/soils. In mixed wastewater effluents from WWTWs it is likely that the necessity for P removal through regular dredging is higher than that from metal accumulation.

## 2.7 pH

pH has a profound effect on the functioning of wetlands, as mentioned in previous sections. Several studies have confirmed the effect of floating vegetated islands in reducing pH. In a two year study by White and Cousins (2013) pH decreased from 8.6 to 6.2. After only 11 days Van de Moortel et al. (2010) found a significant pH decrease from 7.5 to 7.0 whilst the control (without an island) stayed constant at around 7.5. Borne et al. (2013) found a difference between the control (8.3) and the FTW (7.3), which aided Cu adsorption. Interestingly Tanner and Headley (2011) didn't notice a drop in pH in mesocosm tanks, although they still found that treatment was enhanced with floating islands, attributing the difference in to the release of bioactive compounds. The researchers who found differences in pH generally agreed that humic compounds were released by the plants, reducing pH. White and Cousins also acknowledged that alkalinity consumed during microbial nitrification on the plant roots could also be a driving force behind dropping pH within aerobic basins.

## 2.8 Harvesting of Floating Island Plants

FTWs are a relatively new technology with few long term studies, and few details on plant harvesting. The prime functions of plants in FTWs is (i) for their roots to intercept and filter particulates, aiding sedimentation, (ii) to increase the rates of microbiological processes by providing a high surface area on which microorganisms respire, nitrify or denitrify, and (iii) to alter the physico-chemical and chemical environment i.e. increase microbiological processing through the release of humic acids and through reducing DO exchange (acidity and lower oxygen increasing denitrification) and carbon deposition (increasing denitrification). Harvesting is therefore not essential to long term management of FTWs, and although it can help with permanent removal of nutrients and metals, removal rates are typically low. For example, in subsurface flow wetlands plants only removed 2-8% of total nitrogen (Tanner, 2001; Yousefi & Mohseni-Bandpei, 2010) and 3-12% of total phosphorous (Yousefi &

Mohseni-Bandpei, 2010), with microbes believed to be removing the rest of the N, and settling removing the rest of the P. Even with total uptake for N and P estimated at around 6%, all of this is unlikely to be harvested as it is stored in both the roots and shoots, and nutrients are returned back to the wetland through deposition of senescent material.

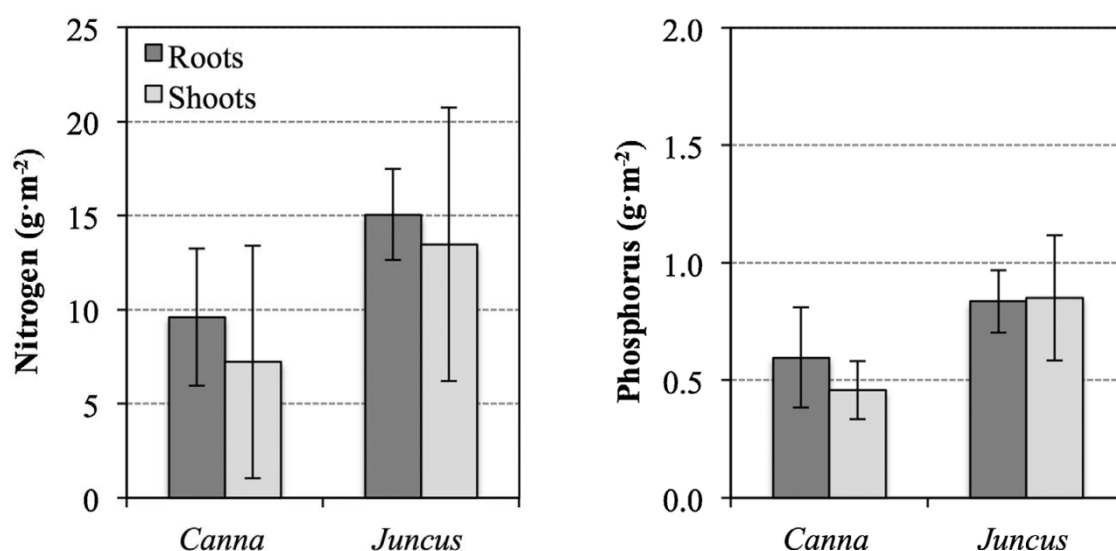
#### *Practicalities of harvesting*

Floating islands facilitate easy harvesting. Often larger islands are able to support the weight of humans, and so cutting could be done directly on the island. Smaller islands can be pulled towards the shore and even lifted out. In contrast with other wetlands where the vegetation is rooted in the sediments, in FTWs both roots and shoots can be removed, and with little disturbance to the sediments. Theoretically a replacement island could be installed immediately, although this may not be cost effective. Also, removal of root mass is likely to be more detrimental to treatment than the gains from permanent removal of the nutrients. For example, FTWs typically increase N and P removal rates by around 20-40% (Table 14), whereas P and N removal by harvesting the whole plant is at the most 6%.

#### *Storage of nutrients in plants*

The start of the growing season, in early spring and prior to maximum growth rate, is the time of highest P uptake. However, prior to autumn senescence, much of the P is relocated to the root stock for the following year (Vymazal, 2007). Thus, if removal of P is a priority, harvest timing and frequency is extremely important, with a recommendation that it is done not only prior to senescence, but also during the peak growth period. The P lost in the senescent material re-enters the basin system very rapidly; up to 30% lost through leaching within the first few days of decomposition (Vymazal, 2007).

Although shoot biomass tends to be larger than root biomass (see plants in design section), there is generally more N, P and K stored in the roots than in the shoots, especially when autumn approaches (White & Cousins, 2013; Winston et al., 2013) e.g. Figure 4.



**Figure 4.** Nitrogen and phosphorus in roots and shoots of *Canna flaccida* and *Juncus effusus* after one summer of growth (harvested 18 September 2008). Nutrients are per m<sup>2</sup> of floating island. Three replicates per bar, with standard error indicated. From White & Cousins (2013).

### *Storage of metals in plants*

Storage of metals tends to show either an even distribution between roots and shoots (e.g. Cu) or predominant storage in the roots (e.g. Zn) (Tanner & Headley, 2011). Table 3 shows uptake of copper and zinc in roots and shoots over a 7 day trial.

**Table 3.** Uptake of copper and zinc in roots and shoots of four different plant species over 7 days in a FTW, measured as  $\mu\text{g}/\text{m}^2/\text{d}$ . Adapted from: Tanner and Headley (2011).

Plant species	Cu		Zn	
	roots	shoots	roots	shoots
<i>Cyperus ustulatus</i>	54	61	3027	282
<i>Carex virgata</i>	54	89	1228	934
<i>Juncus edgariae</i>	38	41	1703	760
<i>Schoenoplectus tabernaemontani</i>	36	24	881	320

### *Relative importance of different processes*

Restricting flow and intercepting particulates on roots is one of the prime benefits of FTWs, consistently removing more BOD and P than open water treatment ponds. However, using synthetic root structure (sisal) Borne et al. (2013) showed that the physical structure alone does not account for most of the benefits of FTWs; water chemistry changes, and to a much lesser extent plant uptake, assist with improving treatment.

### 3. Treatment Efficiency

Treatment efficiency obtained within a FTW is highly dependent on appropriate design and proper operation, as well as the characteristics of the inflow and the objectives of the treatment. At one end of the scale are FTWs designed for aerobic treatment with mixing or air bubbled into the system, often with low % island coverage and addition of calcium carbonate to aid nitrification reactions. These basins are predominantly to remove ammonium. At the other end of the scale are anaerobic basins with up to 100% island coverage, with addition of carbon in the form of e.g. molasses, to supply the denitrification process. Thus, in aerobic basins, ammonium removal may be high whereas nitrate is produced and may exceed inflow nitrate concentrations. In the latter, denitrification reactions remove nitrate, but ammonium may not be nitrified, resulting in  $\text{NH}_4^+$  increasing (due to organic carbon decomposition) such that outflow exceeds inflow. Sometimes floating islands achieve very high rates of removal because of a tightly controlled DO, pH and carbon supply in a hydroponic system. The concentrations of pollutants also affects the removal rate, with higher inflow concentrations often resulting in higher removal rates.

There can be different flow regimes, such as plug flow, where a quantity of effluent is kept in the basin for around 3-7 days, continuous flow, or sporadic flow (such as storm events). Some mesocosm and lab based studies use synthetic effluent with dissolved nutrients, which may exaggerate treatment efficiencies, especially for P and metals which are usually bound to particulates.

Thus, the main considerations when examining performance of a FTW are:

1. Dissolved oxygen: aerobic/anoxic/anaerobic. Natural aeration or artificial aeration through bubblers. With aerobic basins tending to towards nitrification and anaerobic basins tending towards denitrification.
2. Carbon sources: either naturally, through organic carbon, or added artificially, to enhance denitrification rates. Decomposition of organic carbon also results in increased ammonia production within the basin.
3. pH: with alkaline pH increasing nitrification and acidic pH increasing denitrification.
4. Root mass: aiding removal of particulates due to physical filtering and settling processes
5. Mixing: circulation of water to aid the nutrient supply to microbiological processes.
6. Plug flow or continuous flow: affecting residence times and nutrient gradients.
7. Concentrations of inflow pollutants: with higher nutrient supply increasing rates of decomposition/nitrification/denitrification unless limited by another factor.
8. Changes in the FTW chemistry with time. Often pH and redox potential drops due to microbiological processes and restriction of oxygen diffusion from the surface.

Thus, direct comparison between different FTWs has little meaning, and the best comparison is with a relevant control basin. This is often a basin without an island which is receiving the same effluent, however sometimes it is before and after the retrofitting of an island, which doesn't guarantee exactly the same effluent inputs.

New treatment systems can take over a year to stabilise, and even then they can have high variation in treatment efficiency, especially if environmental conditions vary or sinks (such as sediment adsorption) become saturated. However, significantly higher performance of FTWs can be noticed in as little as two days (Van de Moortel et al., 2010), particularly in relation to

nitrification/denitrification and other processes which are predominantly dependent on microorganisms, due to their fast response time (Kadlec & Wallace, 2009).

In this section, treatment efficiency from peer-reviewed FTW studies will be summarised separately, with relevant details supplied, and compared to a control where possible. Where complete columns are blank, there was no information.

Abbreviations follow this system:  $\text{NO}_x$  represents nitrate in the form of either  $\text{NO}_2$  or  $\text{NO}_3$ ; TN is Total Nitrogen;  $\text{N}_{\text{org}}$  is organic nitrogen;  $\text{Cu}_{\text{tot}}$  is total copper;  $\text{Cu}_{\text{part}}$  is particulate copper;  $\text{Cu}_{\text{diss}}$  is dissolved copper; DRP is dissolved reactive phosphorus; BOD is biological oxygen demand; COD is chemical oxygen demand; PBP is Particle Bound Phosphorus; TKN is Total Kjeldahl Nitrogen.

**Table 4.** Removal rates in the study by Van de Moortel *et al.* (2010). Close to 100% coverage of the island resulted in reduced redox potential and anoxic conditions. This resulted in high NO<sub>3</sub> removal rates, but poor NH<sub>4</sub> (thus TN) and P removal rates.

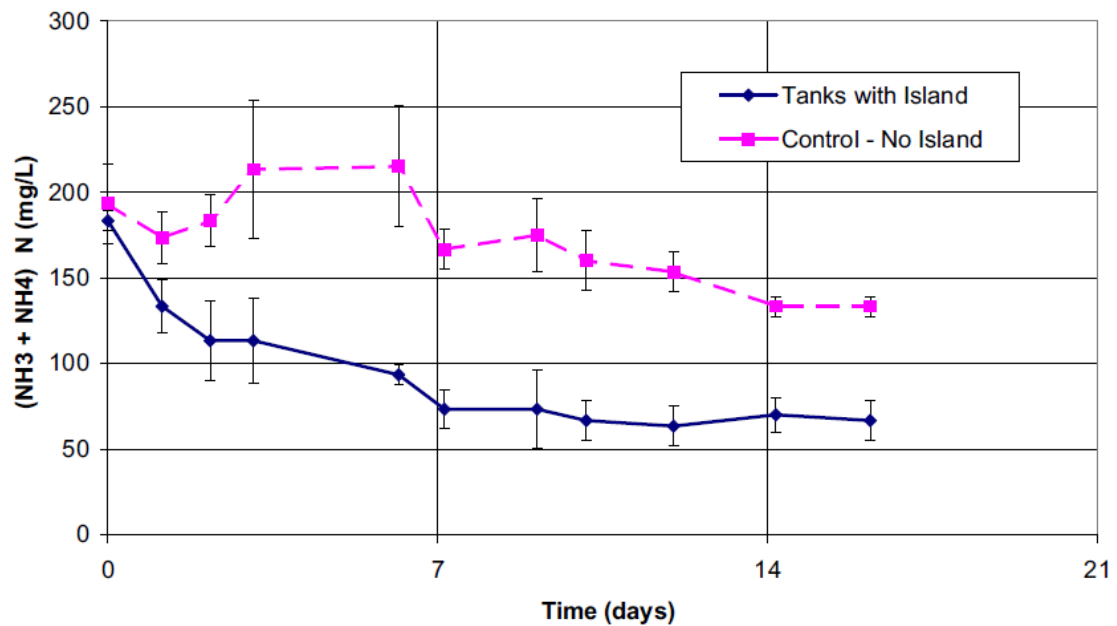
		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/l	2.16	1.77	18		1.9	12
TN	mg/l	21.8	13.1	40	identical	19.5	11
NH <sub>4</sub>	mg/l	16.1	10.8	33	to	16.5	-2
NO <sub>3</sub>	mg/l	0.37	0.2	46	control	0.08	78
N <sub>org</sub>	mg/l	4.31	1.6	63	inflow	2.87	33
TOC	mg/l	27.7	16.4	41		23	17
COD	mg/l	81.3	46.6	43		51.4	37
Cu	mg/l	10.0	5.5	45		8.4	16
Fe	mg/l	454	325	28		259	43
Mn	mg/l	164	153	7		176	-7
Ni	mg/l	10.0	6.1	39		5.75	43
Pb	mg/l	6.10	3.4	44		4.58	25
Zn	mg/l	57.5	29.7	48		47.6	17
SO <sub>4</sub> <sup>2-</sup>	mg/l	64.2	49.8	22		53.7	16
pH	mg/l	7.35	7.08	4		7.48	-2
cond	µS/cm	1035	1017	2		1015	2

**Table 5.** Removal rates in the study by White & Cousins (2013). Troughs of 1.15 m<sup>2</sup> and 3.03 m<sup>2</sup> were used with 100% island coverage and soluble fertiliser added to pond water as the inflow.

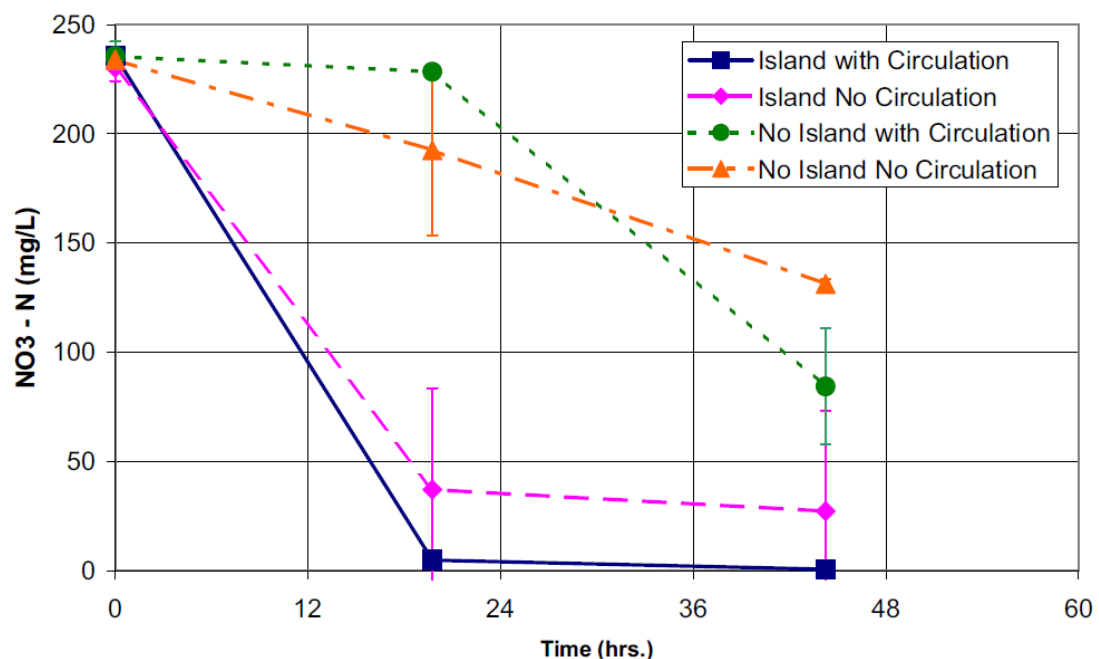
		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/m <sup>2</sup> /day				37.2	15.4	59
TN	mg/m <sup>2</sup> /day				320	106	67

**Table 6.** Removal rates in the study by Yang *et al.* (2008). This was a lab based hydroponic study with synthetic effluent (dissolved P and N, but also organic matter used), although the objective was to represent a nursery run-off treatment system, which naturally has few suspended solids. 100% island coverage was used with purposely anaerobic conditions, 3 day batch process, and glucose added to aid denitrification. Thus, high NO<sub>x</sub> removal rates were obtained, but NH<sub>3</sub> removal was negative as decomposition of organics was still taking place but with limited or no nitrification.

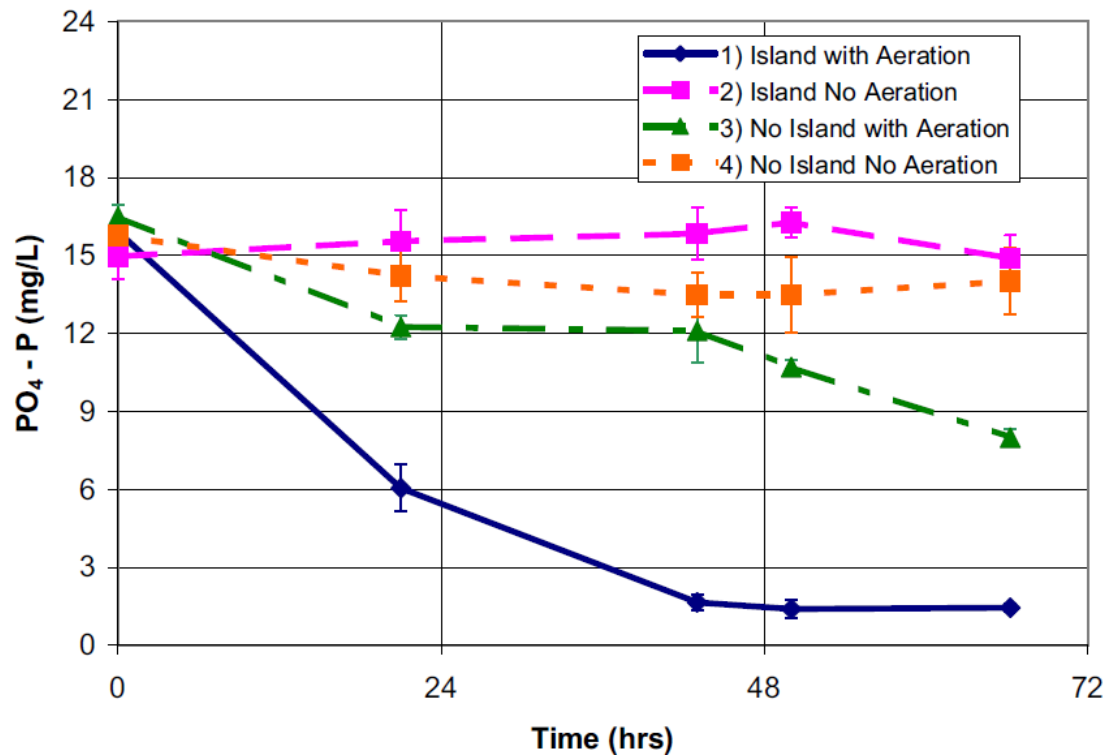
		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/l				1.25	1.17	6
TN	mg/l				3.76	2.59	31
NH <sub>3</sub>	mg/l				0.93	1.19	-28
NO <sub>x</sub>	mg/l				1.39	0.12	91
COD	mg/l				41.8	34.8	17
DO	mg/l				0.01	0	100



**Figure 5.** Ammonium removal rates; graph from the study by Stewart *et al.* (2008). An **aerobic** lab experiment with 100% island coverage, calcium carbonate added, and aerated with a bubbler. Synthetic effluent was created using liquid fertiliser (soluble). Conditions were optimised for ammonium removal.



**Figure 6.** Nitrate removal rates; graph from the study by Stewart *et al.* (2008). An **anaerobic** lab experiment with 100% island coverage and carbon (molasses) added. In some of the replicates water was circulated by a pump. Synthetic effluent was created using liquid fertiliser (soluble). Conditions were optimised for nitrate removal. Redox potential in the control decreased from +200mV to +48mV, but in tanks with islands it decreased to -200mV (much better for denitrification).



**Figure 7.** Phosphate removal rates; graph from the study by Stewart *et al.* (2008). Both **anaerobic and aerobic** basins were tested (conditions as in Figures 5 and 6) without islands and with 100% cover of islands. Phosphate removal was best achieved when there was both aeration and floating islands.

**Table 7.** Removal rates in the study by Borne *et al.* (2013). A control stormwater retention pond was compared with a retention pond with 50% cover of floating island, receiving the same effluent. Data was retrieved from a graphical presentation of inflow and outflow effluent concentrations.

	control			FTW		
	inflow	outflow	% removal	inflow	outflow	% removal
TSS	30	24	20	identical	12	60
Cu <sub>tot</sub>	0.0090	0.0075	17	to	0.0057	37
Cu <sub>part</sub>	0.0035	0.0030	14	control	0.0019	46
Cu <sub>diss</sub>	0.0049	0.0044	10	inflow	0.0038	22
Zn <sub>tot</sub>	0.035	0.022	37		0.013	63
Zn <sub>part</sub>	0.027	0.017	37		0.010	63
Zn <sub>diss</sub>	0.006	0.005	17		0.005	17



**Table 8.** Removal rates in the study by Tanner & Headley (2011). After 7 days batch experiment with 1m x 1m mesocosms and 36% island cover. Artificial stormwater used. FTW results are from the plant species which gave best results (*Cyperus ustulatus*).

	control			FTW		
	inflow	outflow	% removal	inflow	outflow	% removal
TP			3			58
DRP			-5			60
Cu <sub>tot</sub>			7			57
Cu <sub>diss</sub>			5			50
Zn <sub>tot</sub>			-1			19
Zn <sub>diss</sub>			1			37
Turbidity - subsurface			24			67
Turbidity - bottom			24			67
DO (subsurface)			8			39
DO (bottom)			11			40

**Table 9.** Removal rates in the study by Stefani *et al.* (2011) based on median values. Effluent was from aquaculture, following conventional activated sludge treatment. There was a 19% cover of islands and a continuous flow (0.09 m/s).

		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/l				0.55	0.19	65
SS	mg/l				350	320	9
COD	mg/l				15	5	67
BOD	mg/l				4.2	2	52
pH					7.3	7.2	1
cond	µS/cm				645	645	0

**Table 10.** Removal rates in the study by Winston *et al.* (2013). The study examined a stormwater retention pond before (control) and after (FTW) retrofitting an **18%** coverage of floating island. Data is a mean over different storm events.

		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/l	0.26	0.11	58	0.41	0.05	88
PBP	mg/l	0.13	0.04	69	0.17	0.03	82
OP	mg/l	0.13	0.07	46	0.24	0.02	92
TN	mg/l	1.01	0.41	59	3.49	0.43	88
NH <sub>3</sub>	mg/l	0.10	0.05	50	1.6	0.04	98
TKN	mg/l	0.88	0.35	60	3.32	0.37	89
NO <sub>x</sub>	mg/l	0.12	0.06	50	0.17	0.06	65
N <sub>org</sub>	mg/l	0.89	0.34	62	1.72	0.33	81
TSS	mg/l	216	24	89	252	13	95

**Table 11.** Removal rates in the study by Winston *et al.* (2013). The study examined a stormwater retention pond before (control) and after (FTW) retrofitting an 9% coverage of floating island. Data is a mean over different storm events.

		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/l	0.26	0.17	<b>35</b>	0.19	0.12	<b>37</b>
PBP	mg/l	0.13	0.05	<b>62</b>	0.07	0.05	<b>29</b>
OP	mg/l	0.14	0.12	<b>14</b>	0.12	0.07	<b>42</b>
TN	mg/l	1.64	1.05	<b>36</b>	1.17	0.61	<b>48</b>
NH <sub>3</sub>	mg/l	0.12	0.11	<b>8</b>	0.11	0.05	<b>55</b>
TKN	mg/l	1.43	0.97	<b>32</b>	0.84	0.55	<b>35</b>
NO <sub>x</sub>	mg/l	0.20	0.08	<b>60</b>	0.34	0.06	<b>82</b>
N <sub>org</sub>	mg/l	1.50	0.93	<b>38</b>	0.72	0.5	<b>31</b>
TSS		354	30	<b>92</b>	101	22	<b>78</b>

**Table 12.** Removal rates in the study by Chang *et al.* (2013) **during** storm events in a functioning stormwater retention pond; assessed before (control) and after (FTW) fitting floating islands with 8.7% cover. Nutrient concentrations are given as the means over several different storm events. The pond contained a fountain.

		Control			FTW		
		inflow	Outflow	% removal	inflow	outflow	% removal
TP	mg/l	0.028	0.027	<b>4</b>	0.058	0.050	<b>14</b>
OP	mg/l	0.006	0.006	<b>0</b>	0.021	0.010	<b>52</b>
TN	mg/l	0.300	0.377	<b>-26</b>	0.626	0.526	<b>16</b>
NH <sub>3</sub>	mg/l	0.048	0.052	<b>-8</b>	0.102	0.104	<b>-2</b>
NO <sub>x</sub>	mg/l	0.006	0.017	<b>-183</b>	0.062	0.029	<b>53</b>

**Table 13.** Removal rates in the study by Chang *et al.* (2013) **outside** of storm events in a functioning stormwater retention pond; assessed before (control) and after (FTW) fitting floating islands with 8.7% cover. Nutrient concentrations are given as the means over different sampling times. Notice that the treatment rates are much higher than during storm events (probably due to lower flows and thus higher retention times).

		control			FTW		
		inflow	outflow	% removal	inflow	outflow	% removal
TP	mg/l	0.037	0.034	<b>8</b>	0.055	0.029	<b>47</b>
OP	mg/l	0.003	0.002	<b>33</b>	0.020	0.004	<b>80</b>
TN	mg/l	0.303	0.349	<b>-15</b>	0.655	0.552	<b>16</b>
NH <sub>3</sub>	mg/l	0.121	0.103	<b>15</b>	0.208	0.102	<b>51</b>
NO <sub>x</sub>	mg/l	0.025	0.022	<b>12</b>	0.032	0.025	<b>22</b>

### Overview

With more cover of floating islands there is a tendency for redox potential to drop due to reduced O<sub>2</sub> diffusion from atmosphere. This leads to denitrification processes dominating in which there is high removal of NO<sub>3</sub> but low removal of NH<sub>4</sub> (Yang et al., 2008; Van de Moortel et al., 2010). Indeed NH<sub>4</sub> removal may be negative due to decomposition of organics to NH<sub>4</sub> without subsequent removal by nitrification (Table 4 and 6). Aeration can prevent this NH<sub>4</sub> accumulation by encouraging nitrification, and it also prevents P release from sediments that can occur at low redox potentials (Figure 7).

Low % island cover had detrimental effects on treatment efficiency, as did lower residence times. For example, TN removal was 48% with 9% island cover in the Winston et al. study (2013), but this increased to 88% TN removal with 18% cover (Tables 10 and 11). Similarly Chang *et al.* (2013) found only 14% TP removal with 9% cover during storms, but outside of storm flows this removal increased to 47% (Tables 12 and 13).

Around 20% cover seems optimal if the basin is to be maintained as an aerobic system without artificial aeration, and still achieve good removal efficiency. Beyond this point it is probably worth using 100% cover, with a choice between a high nitrate removal anaerobic basin, or artificial aeration (bubbling) to produce a high treatment rate aerobic basin. Stewart et al. (2008) illustrates how tightly controlled conditions and addition of calcium carbonate (nitrification) or carbon (denitrification) can be used to optimise treatment rates. Stewart et al. (2008) also showed that nitrification and denitrification processes can be achieved in a single aerobic tank if tightly controlled. Treatment efficiencies noted by Stewart and White & Cousins (2013) are likely to be around the maximum achievable in FTWs due to the use of soluble fertilisers in their experiments and their tightly controlled hydroponic systems. Therefore when assessing potential performance of a new FTW we must decide whether it will be a tightly controlled situation or more of a field based FTW.

Table 14 summarises these studies. The improvements through using Floating Islands, as discussed, vary due to conditions, however we can expect between around 2 and 55% increase in P removal compared to a Free Water Surface wetland, and a 12 to 42% increase in N removal. Metal removal is also considerably higher in FTWs (20-50% higher). Most importantly, if conditions are tailored for denitrification (anaerobic and sufficient carbon supply) NO<sub>3</sub> removal can be up to 100% in FTWs.

**Table 14.** Summary of % removal rates in different studies for main nutrients and metals. 'Improvement' examines the increase of treatment efficiency of FTWs beyond the control wetlands (FST wetlands). The Van de Moortel study is excluded from the final comparison since anaerobic conditions produced P release and is not an example of good FTW management.

Study		Moortel	White	Yang	Stewart*	Stewart*	Borne*	Tanner	Stefani	Winston	Winston	Chang	Chang	RANGE
% cover		100	100	100	100	100	50	50	19	18	9	8.7	8.7	8.7-100
notes		anaerobic	anaerobic	anaerobic	aerobic	anaerobic						storm	non-storm	
FTW	TP	12	59	6	91			58	65	88	37	14	47	6-91
	TN	11	67	31						88	48	16	16	11-88
	NH <sub>4</sub>	-2		-28	66					98	55	-2	51	-28-66
	NO <sub>3</sub> /NO <sub>x</sub>	78		91		100				65	82	53	22	22-100
	Cu <sub>tot</sub>	16					37	57						16-57
	Zn <sub>tot</sub>	17					63	19						17-63
controls	TP	18			53			3		58	35	4	8	3-58
	TN	40								59	36	-26	-15	-26-59
	NH <sub>4</sub>	33			26					50	8	-8	15	-8-33
	NO <sub>3</sub> /NO <sub>x</sub>	46				42				50	60	-183	12	-183-60
	Cu <sub>tot</sub>	45					17	7						7-45
	Zn <sub>tot</sub>	48					37	-1						-1-48
improvement	TP				38			55		30	2	10	39	2-55
	TN									29	12	42	31	12-42
	NH <sub>4</sub>				40					48	47	6	36	6-48
	NO <sub>3</sub> /NO <sub>x</sub>					58				15	22	236	10	10-236
	Cu <sub>tot</sub>						20	50						20-50
	Zn <sub>tot</sub>						26	20						20-26

Notes:

(\*) indicates data extracted from graphs.

In Stewart study, PO<sub>4</sub><sup>3-</sup> was assessed instead of P

### 3.1 Seasonal Variation

Seasonal variation in FTW is due to (i) temperature variations, which affect plant and especially microbial productivity, (ii) consequent DO variations due to increased oxygen demand when there is increased microbiological activity, and to some extent the solubility of oxygen in water at different temperatures, and (iii) seasonal growth patterns in plants.

The effect of season on treatment efficiency depends on the main processes involved in their removal, particularly how temperature and oxygen variations affect these processes. For example, spring and autumn are peak P uptake periods for vegetation in wetlands (Kadlec & Wallace, 2009) however, the main process of P removal is settling and adsorption, so seasonal P removal was found to vary less than that of nitrogen (Wittgren & Maehlum, 1997).

Studies have shown conflicting results over how variable treatment efficiency is over different seasons, particularly with N removal, but this is likely to be due to differences in limiting factors. As previously mentioned, plant uptake as  $\text{NO}_3$  or  $\text{NH}_4^+$  tends to be relatively small compared to microbiological processes (Riley et al., 2005). Thus, studies have found N removal to be affected by seasonal temperature variation (Spieles & Mitsch, 2000; Picard et al., 2005). However, Maehlum and Stalnacke (1999) and Mander et al. (2000) found little difference in N removal between warm and cold climates and Van de Moortel et al. (2010) found more variation due to temperature in P than in N. It is likely that these differences are due to other factors that may be limiting, particularly anoxia. For example, in the study by Van de Moortel et al. (2010) there was low  $\text{NH}_4$  removal as 100% island coverage produced low DO and reducing conditions, nullifying any further potential N removal increases due to increased temperature. Also, as mentioned previously, in practice decomposition is not found to be highly temperature dependent in wetlands (Akratos & Tsihrintzis, 2007; Kadlec & Wallace, 2009) and therefore ammonia production rates are not likely to change much with temperature. Thus, interactions between season, light, temperature and DO mean that an individual variable is not a good predictor of activity, and the net effect can be counter-intuitive (Stein & Hook, 2005; Kadlec & Wallace, 2009). However, despite these interacting effects very low temperatures (5 °C) certainly restrict microbiological activity and plant growth (Mitsch and Gosselink 1993).

#### *Rainfall*

Rainfall can have a large and varied effect on pollutants entering a basin. If the inflow is from a combined sewer system rainfall events can massively increase dilution and flow rates into the wetland. Van de Moortel et al. (2010) found that heavy rainfall caused a significant reduction in inflow conductivity from 1102  $\mu\text{S}$  to 733  $\mu\text{S}$ , and total nitrogen from 23.1 mg TN/l to 16.9 mg TN/l. Then, after rain events although other constituents remained diluted in the pond, ammonium and nitrate concentrations actually increased (probably due to microbiological activity). With stormwater treatment ponds, the inflow comes from road run-off which has often had an accumulation of metals during the dry period, so initial concentrations during a storm are usually high, as the metals and particulates get washed off the road, but then rapidly decrease as the storm continues and the concentrations become diluted (Barbosa & Dodkins, 2010).

Rainfall and evaporation also have an effect on dilution within the basins (Kadlec & Wallace, 2009). The addition of rainwater can alter the water chemistry (oxygen, pH), rates of microbiological activity, and affect physical processes e.g. increased depth increasing settling. It is also important to consider that when measuring inflow and outflow concentrations, differences may be due to changes in dilution, rather than any removal within the basin, and

loading capacities must take rainfall input and evaporation (and drainage) into consideration (Kadlec & Wallace, 2009).

#### *Shading and Temperature*

Floating islands can significantly reduce water temperature (by shading) in the warmer months, and also reduce temperature variation if there is sufficient cover (Van de Moortel et al., 2010). However, Winston et al. (2013) with only 18% island cover, found there was little water temperature reduction (preventing them producing conditions for trout to live in the FTW). Van de Moortel et al (2010) also found that although summer temperatures were lower in FTW compared to open water wetlands, winter temperatures were not lower. However, ice still persisted longer in FTWs during the winter due to reduced wind disturbance at the surface in FTWs.

## 4. Design Considerations

To achieve treatment objectives careful consideration must be taken in design and operation of the wetland. These must be specific to the flow volume, flow variation, the concentrations of pollutant and the required characteristics of outflow. Wetlands can easily be overloaded with sludge so pre-treatment (removal of large material by bar screen or settling of grit and stones) and primary treatment (sedimentation) are essential for domestic effluents prior to entering the wetland. Good design of these initial stages is also extremely important in maximising the treatment efficiency and the cost of running a FTW and to prevent them becoming unnecessarily clogged by high sludge loadings.

### 4.1 Island Cover

Since floating islands can restrict oxygen diffusion from the air into the water (Smith & Kalin, 2000), island coverage is an extremely important design factor. For example, an almost complete coverage by islands resulted in poor P retention in sediments due to anoxia (Van de Moortel et al., 2010).

The percentage cover of a pond by the island is one of the most important considerations in FTW design. High cover (>50%) can cause anoxia but low cover (9 to 18%) may produce little additional treatment effect (e.g. Winston et al., 2013). The anoxia is not only caused by islands reducing air-water contact, but also because of the high rate of microbiological processes such as nitrification and decomposition. Thus, the optimum size of the island to prevent anoxia is likely to be dependent on the quality of the influent, particularly ammonia/nitrate and organic carbon concentrations. Flow design, mixing and aeration will also be major factors (See section 3. Treatment Efficiency).

Using more island coverage should increase microbiological activity due to the larger root area, however if high rates of aerobic microbiological activity is to be maintained (e.g. nitrification) oxygen consumption will necessarily be high. To maintain high island coverage without depleting oxygen, bubblers can be installed (Stewart et al., 2008). This requires investment and energy costs, and therefore their use depends on a cost-benefit analysis, although energy can be provided by e.g. solar power. Baffles have also been introduced in some FTWs to increase circulation around the roots. Mixing waters to promote aeration should be done with care as disturbance of sediments can liberate trapped P.

### 4.2 Optimising for N removal

Since P is effectively conservative, but N can be released as gas through correctly managing the microbial environment, strategies for permanently removing N are very different from those for removing P.

#### *Aerobic and Anaerobic basins*

Floating islands may increase denitrification by increasing anoxia, although it is preferable to have an oxygenated basin with a high residence time as a first stage to convert most of the ammonia to nitrate in the nitrification process.

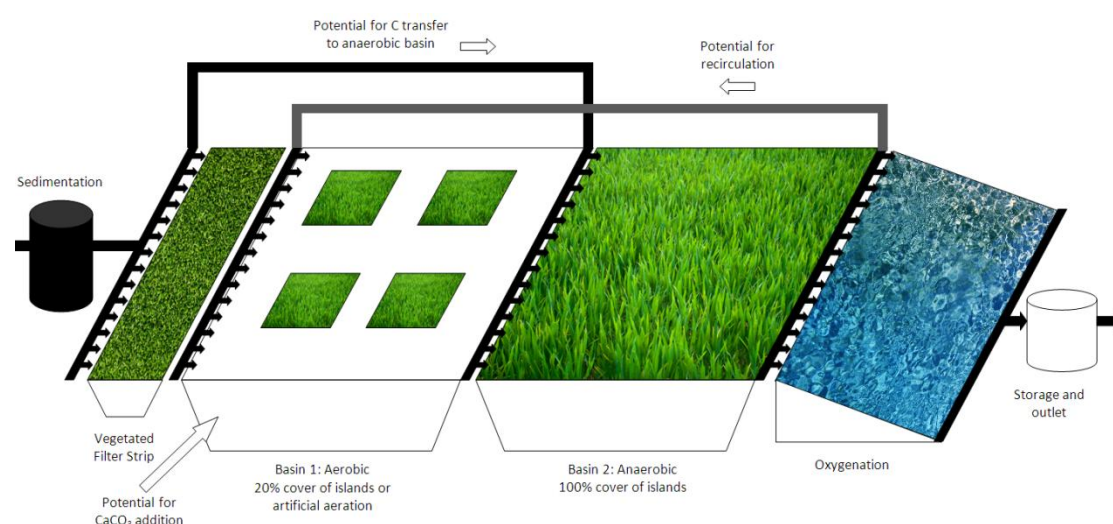
Thus, with N the main objective is to convert as much ammonium as possible to nitrate, usually through an aerobic 1<sup>st</sup> stage, and then to convert as much of this nitrate to N<sub>2</sub> gas, through an anoxic 2<sup>nd</sup> stage. Oxygen in the aerobic stage can be rapidly depleted with high coverage of FIs and high rates of microbiological activity, so FI cover has to be carefully managed, or artificial aeration has to be included. Sufficient alkalinity must also be available for nitrification, which can be achieved through the addition of CaCO<sub>3</sub> (Stewart et al., 2008).

Nitrification reduces DO and pH, though these conditions are ideal for the next (anoxic) denitrification stage. FI cover can be much higher at this stage. Yang et al. (2008) achieved 97% N removal rates with 0% DO in a hydroponic system, though in more natural systems anoxia can cause sulphide toxicity (Lamers et al., 2002) that kill or restrict root growth.

### Recycling

Denitrification is predominantly limited by C supply, with a recommended C:N loading ratio of 5:1 (Bishay & Kadlec, 2005). In a two stage system Carbon limitation often occurs because much of the organic C is removed by settling in the earlier aerobic stage (Kadlec & Wallace, 2009), thus releasing nitrate. Additional C can be supplied artificially, e.g. as glucose syrup (Yang et al., 2008) but for most effluent treatment systems it is cheaper and more practical to seed the anoxic basin with raw effluent that has not gone through the anaerobic stage (Kadlec & Wallace, 2009).

Recycling is also used to return anaerobic outflow back to the aerobic stage; denitrification makes the effluent more alkaline, ideal for further nitrification of ammonia (Kadlec & Wallace, 2009). Recycling is now in Danish treatment wetland guidelines (Brix & Schierup, 1990). Figure 5 gives an example of how FTW wetlands could be designed for treatment of domestic effluent, including recycling.



**Figure 5.** A theoretical design using FTWs for treating low volume domestic effluent (mixture of P, BOD,  $\text{NH}_4^+$  and  $\text{NO}_3^-$  inputs) showing basic design features of combined basins. The vegetated filter strip would have to be adapted/increased/removed depending on solids input from sedimentation.

### 4.3 Plants

The treatment potential within a FTW depends mostly on the filtering capacity of the roots (root depth and density) and their surface area as a microbiological habitat. Choice of plant species will also affect the rates of nutrient and metal uptake, root/shoot biomass division, growth rates and the way in which the basin water chemistry is altered due to the release of humic acids and protons by plant roots.

#### Plant dimensions

Tanner & Headley (2011) examined four species growing on floating islands in mesocosms, providing detailed measurements. 90<sup>th</sup> percentile of root depth averaged between 24 and 48cm, depending on species. The root surface area was between 4.6 and 9.3  $\text{m}^2/\text{m}^2$  of floating mat. Above mat biomass was between 834 and 2350  $\text{g}/\text{m}^2$  and root biomass of 184-



533 g/m<sup>2</sup> (see Table 3 for more details) with shoot to root ratios of between 3.7 and 4.5. Winston *et al.* (2013) found that *Hibiscus* had shoot:root ratio of 6.3. Indeed, most species have an above mat biomass greater than the below mat biomass, except for *Carex* spp. such as *Carex stricta* (Winston *et al.*, 2013), *Carex virgata* and *Cyperus ustulatus* (Tanner & Headley, 2011) (Table 3).

**Table 5.** Mean biomass and shoot:root ratio for FTW plants.

Plant species	Shoots: Mean above mat biomass (g/m <sup>2</sup> )	Roots: Mean below mat biomass (g/m <sup>2</sup> )	Biomass ratio
<sup>1</sup> <i>Juncus</i> spp.	86.3	43.4	2.0
<sup>1</sup> <i>Carex stricta</i>	131.4	207.6	0.6
<sup>1</sup> <i>Spartina pectinata</i>	121.7	48.1	2.5
<sup>1</sup> <i>Hibiscus moscheutos</i>	269	58.9	4.6
<sup>1</sup> <i>Pontederia cordata</i>	72	57.7	1.2
<sup>2</sup> <i>Cyperus ustulatus</i>	1528	329	4.6
<sup>2</sup> <i>Carex virgate</i>	2350	533	4.4
<sup>2</sup> <i>Juncus edgariae</i>	1113	299	3.7
<sup>2</sup> <i>Schoenoplectus tabernaemontani</i>	834	184	4.5

<sup>1</sup> Winston *et al.* (2013) in stormwater retention pond

<sup>2</sup> Tanner & Headley (2011) in mesocosm with much more intensive planting

Plant uptake appears to be more associated with total plant biomass rather than root density (Tanner & Headley, 2011), although White & Cousins (2013) found that uptake of N and P by *Juncus effusus* (60.6 N and 3.71 g P/m<sup>2</sup>/growing season) was higher than that of *Canna flaccida* (3.71 N and 2.27 g P/m<sup>2</sup>/growing season) despite having a similar shoot length, and this was attributed to the much longer roots of *J. effusus*. Nutrient uptake by *J. effusus* was also found to be much higher than that of *Pontederia cordata* in a study by (Chang *et al.*, 2013).

Floating islands are usually allowed 6 months of plant growth to establish before assessing efficiency e.g. (Borne *et al.*, 2013). Once plant growth has reached a maximum (maximum density and shoot biomass) there is no additional net uptake of nutrients by the plants i.e. litter deposition is equal to growth (Kadlec & Wallace, 2009). However, although some of this litter will accumulate on the island, some will sink into the basin with some nutrient release but also with some C and P storage in the sediments.

White & Cousins (2013) found that an increase in nutrient loading increased shoot growth (but not root growth) and suggested that this may be due to a shift in allocation strategy towards shoots when nutrients are plentiful, following Muller, Schmid & Weiner (2000). However, harvesting of the shoots does not appear to affect the root biomass (Borne *et al.*, 2013).

#### *Plant establishment*

Vogel (2011) noted that floating island plants have more establishment success and establish quicker, with more cover, when the starting biomass is higher. She recommends planting of as much biomass stock as possible at the start, to aid establishment. The growth rate for

some plants may be higher in the first year of establishment, whilst other plants may have higher growth rate in the second year (Svengsouk & Mitsch, 2001).

#### *Buoyancy of islands*

Buoyancy of vegetated islands changes seasonally, with mats sinking several centimetres during the spring and summer as the biomass increases (Hogg and Wein 1988 a). Seasonal effects become less pronounced with age, as dead biomass accumulates and decomposition increases (matching biomass accumulation).

#### **4.4 Activated Carbon**

Activated carbon is being considered by Frog Environmental Ltd. as a possibility for improving floating island performance prior to the complete establishment of plants by incorporating the carbon within the floating island material. Performance of floating islands usually relates to their ability to increase removal rates for P and N as well as to remove metals, commonly Cu and Zn.

Activated carbon is used in water filters and chemical purification processes. It is highly porous carbon with a high surface area which has been treated by oxygen or sulphuric acid to increase adsorption. It has a surface area of 300-2,000 m<sup>2</sup>/g and can adsorb a wide range of pollutants including large organic molecules. Because adsorption works by chemically binding the impurities to the carbon, the active sites in the carbon eventually become filled and adsorption stops. The effectiveness of activated carbon depends on pore size, the carbon source and the manufacturing process.

Typically activated carbon is used to remove metals or organic pollutants rather than nutrients. This is because the surface of activated carbon is negatively charged, attracting positive ions (e.g. Cu<sup>2+</sup>, Zn<sup>2+</sup>) rather than negative ions (NO<sub>2</sub><sup>-</sup>, NO<sub>3</sub><sup>-</sup>). Bhatnagar & Sillanpää (2011) reviewed the adsorption of nitrate on to various carbon substances. Results vary with 1mg/g (Mizuta et al., 2004), 1.7 mg/g (Bhatnagara\* et al., 2008) and 4 mg/g (Oztürk & Bektaş, 2004) adsorption of NO<sub>3</sub><sup>-</sup>, although these studies are all done in lab conditions and are better than can be expected in the field. Biochar (a form of charcoal) has been tested in field for nitrate removal, though it has tended to have low effectiveness except where nut shells have been the carbon source of biochar (Knowles et al., 2011; Yao et al., 2012).

Nitrate adsorption depends on contact time. Oztürk and Bektaş (2004) achieved complete adsorption within 1 hour at pH<5.0 and 25 °C. Optimal pH for activated carbon adsorption of nitrate occurs at pH2. This is because H<sup>+</sup> ions bind to surface and reduce -ve charge, increasing uptake of -ve ions (NO<sub>3</sub><sup>-</sup>). Problems with extrapolating these results to the field include (i) the nitrate could be bound to other substances within the water column or sediments, (ii) there would be a diffusion gradient between the site of adsorption (the island) and the bottom of the basin, (iii) the effluent is not being passed through the carbon, so adsorption is passive (iv) optimal pHs for adsorption would not be suitable for a treatment basin, which should be kept around neutral pH.

Ammonia adsorption is around 5.08 mg NH<sub>3</sub>/g of carbon at 20 °C increasing to 5.80 mg/g at 60 °C (Long et al., 2008). The temperature of activation of the carbon also affects the adsorption capacity, with higher activation temperatures increasing ammonia adsorption (Ghauri et al., 2012).

P removal in wetlands tends to be predominantly through physical sedimentation processes, which are aided by particle interception by plant roots. When P removal was tested with activated carbon adsorption capacity was 1.11 mg /g at high P concentrations, decreasing

with lower P concentrations (Liang et al., 2011). Optimum pH for adsorption ranges between 6 and 10 (Kumarab et al., 2010), which is ideal for FTWs, although again, these studies use data for filtration of nutrients rather than passive adsorption at the surface of the basin.

Adsorption rates of different nutrients are dependent on the nutrient concentration in the effluent, and at low concentrations close to 100% removal is theoretically possible. However, with low circulation and a diffusion gradient within a treatment basin it is unlikely that high percentage removal rates are possible. In addition, we would expect to use around 100 times more carbon (by weight) than the nutrient we are reclaiming, which is likely to be prohibitively expensive.

Activated carbon can provide a carbon source for improving denitrification when C is limiting (Isaacs & Henze 1995; Yang *et al.* 2008). This may be particularly important prior to the establishment of vegetation, which would then provide a source of carbon through decaying organic matter. However, addition between the layers of the floating island may be less useful than simply mixing the powdered activated carbon into the effluent as it enters the basin. Also, a soluble carbon source such as glucose (Yang et al., 2008), acetate or hydrolysate (Isaacs & Henze, 1995) may be better for encouraging denitrification than powdered activated carbon.

## 5. Conclusions and Recommendations

The main function of floating islands in removing pollutants from effluents is:

- Plant roots assisting in filtering and settling processes for P
- Plant roots acting as a large surface area for micro-organism activity in: decomposition, nitrification, and denitrification (removal of BOD and N).
- Mild acidification of water due to release of humic acids, and a C input from senescent vegetation; assisting denitrification.

P removal is predominantly a physical process. It binds to particulates and removal is assisted by the reduced water movement and the filtering effect of roots on these particulates. This sloughs off to the bottom sediments. Metals are also removed predominantly through binding to particles and sedimentation. Reduced DO in the basin and disturbance of the sediments can result in release of P and metals from the sediments. P is effectively conservative, and if dredging of the sediments is not done (around every 10 years is suggested) the sediment bound P and dissolved P will reach an equilibrium whereby there is no net P removal (and potential for pulses of P in the outflow which are higher than that in the inflow).

N removal is predominantly a microbiological process with  $\text{NH}_4^+$  being nitrified to  $\text{NO}_3^-$  in aerobic basins by nitrifying bacteria, then  $\text{NO}_3^-$  being denitrified to  $\text{N}_2$  gas (and thus released) in anaerobic basins by denitrifying bacteria. FTWs have excellent potential for removing N from effluents. An initial aerobic basin (up to 20% island cover or 100% with aeration) can be used for nitrification and then a second anaerobic basin (100% island cover) can be used for denitrification. Up to 100% N removal is possible, with more tightly controlled conditions increasing the ability to remove N. At the aerobic stage the addition of  $\text{CaCO}_3$  can assist with nitrification (as alkalinity is used up during this process). At the anaerobic stage the addition of C can assist with denitrification (as carbon compounds are used during this process). This C may be added as e.g. glucose or molasses, or as BOD fed from the FTW inlet.

With good management but without hydroponic conditions (i.e. aeration,  $\text{CaCO}_3$  or artificial C addition) we could expect a FTW wetland to achieve around 60% removal of TP, 75% removal of TN, 50% removal of  $\text{NH}_4^+$ , 80% removal of  $\text{NO}_3^-$  and 40% removal of metals. All these are expected to be significant improvements (around 20-40% higher) than with basins without islands, depending on specific conditions. More controlled conditions could considerably increase the treatment rates.

Plant uptake only accounts for up to 6% of nutrient (N and P) removal in FTWs. This is also recycled into the system through decomposition unless harvesting is undertaken. Although concentrations of nutrients and some metals (e.g. Zn) are higher in the roots, shoot biomass of plants tends to be higher. Thus shoot harvesting often removes a little over half of the nutrients taken up by the plants. Floating islands also provide access for root harvesting, but harvesting of roots is unlikely to be beneficial as it is more time consuming and also reduces the filtering capacity and microbiological activity associated with the root network: the principal mechanisms of nutrient removal in FTWs. Evidence suggests that removal of shoots does not negatively affect the roots.

FTWs have other advantages over conventional Free Water Surface Wetlands:

- They can adjust to varying water levels

- A higher retention time is possible as they can be made deeper without submerging the vegetation
- Habitat value for birds/amphibians

#### *Recommendations for domestic effluent treatment:*

Domestic effluent usually has high BOD,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and P although specific operation and design of FTWs should be tailored to the specific characteristics of the inflow.

1. N removal is the principal benefit of FTWs:
  - An aerobic basin for nitrification is required to convert ammonia to nitrate
  - An anaerobic basin for denitrification is required to convert nitrate to  $\text{N}_2$  gas.
  - Although nitrification and denitrification can be achieved in the same basin, separate aerobic/anaerobic basins can be used to more easily control the processes.
2. Depending on cost considerations and inflow water alkalinity,  $\text{CaCO}_3$  can be added in the aerobic basin to aid nitrification.
3. C can be added in the anaerobic basin to aid denitrification. In smaller treatment systems requiring high water quality outflow a hydroponic system with glucose or molasses addition can be used. For larger treatment systems with greater costs considerations, input of C can come from a controlled input of BOD directly from the FTW inflow.
4. 100% cover of islands, with mixing, is optimal for N reduction in the anaerobic basin.
5. 100% cover of islands with aeration (bubbling) is optimal for aerobic nitrification. If cost considerations prevent aeration, 20% island cover is recommended in the aerobic basin to prevent anoxia occurring.
6. A recycling system from the anaerobic to the aerobic basin, although not always necessary, may be useful when there is excessive  $\text{NH}_4^+$  in the outflow i.e. to increase nitrification rates.
7. Aeration is required after the denitrification basin to prevent the release of anoxic waters to the environment.
8. Circum-neutral pH should be maintained in anaerobic and aerobic basins. If pH drops considerably there is a danger of P release.
9. Dredging, particularly of the first (aerobic) basin is recommended every 10 years to remove P trapped in sediments, as well as accumulating metals. Alternative (dormant) treatment basins may be required to be made operational treat effluent as dredging operations are undertaken in the main basin.
10. Plants with high root surface area and high plant biomass are recommended for the floating islands e.g. *Juncus effusus*. Ecological considerations may result in other species being chosen or plant mixtures being used.
11. Harvesting should be done, but only of the shoots.

#### *Use of Activated Carbon*

The use of activated carbon between layers of floating island material to assist in pollutant removal will probably have limited effectiveness. This is due to a diffusion gradient between the surface of the basin and the bottom of the basin, and the passive nature of adsorption i.e. the effluent is not being filtered through the medium. At the very most (with high retention times and full adsorption) N and P removal is likely to be about 1g for every 100g of activated carbon used. The proper establishment of plants, a focus on correct basin design, and water chemistry control, is likely to be a much more effective use of resources.

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**(1) Articles Published in Scientific Journals (typically  
peer-reviewed)**

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**Floating Treatment Wetlands (FTWs) in Wastewater  
Treatment: Treatment efficiency and potential benefits of  
activated carbon.**

<b>Type</b>	Review of Published Articles
<b>Author</b>	Dodkins, I; Mendzil, AF; O'Dea, L.
<b>Publication</b>	unpublished
<b>Volume</b>	n/a
<b>Pages</b>	n/a
<b>Date</b>	March 2014

**Notes:**

This report was prepared by Swansea University staff for FROG Environmental, Ltd. It includes historical information and discussions of treatment efficacies for common contaminants studied by numerous researchers. Detailed information is provided for the various pathways for phosphorus removal (Section 2.1), nitrogen removal (Section 2.2), oxygen issues and effects (Section 2.3 – 2.4); BOD, suspended solids and carbon (Section 2.5), metal removal (Section 2.6), plants (Section 2.8), and other factors related to FTW operation.

The report describes methods for optimizing removal of specific contaminants by controlling aeration and pH, determining percent island coverage, using chemical additives, etc.

**Executive Summary:**

*Floating Treatment Wetlands (FTWs) have many benefits over Free Water Surface (FWS) wetlands:*

- 1. Plant roots assisting in filtering and settling processes for sediment bound P and metals*
- 2. Plant roots acting as a large surface area for micro--organism activity in:*

*decomposition, nitrification, and denitrification (removal of BOD and N).*

- 3. Mild acidification of water due to release of humic acids; and a C input from senescent vegetation, assisting denitrification.*
- 4. They can adjust to varying water levels*
- 5. A higher retention time is possible as they can be made deeper without submerging the vegetation*

*Percentage removal of nutrients and metals from effluent is around 20-40% higher in FTWs than in conventional FWS ponds. Removal efficiency, particularly of nitrogen, can be further increased with tighter control on the water chemistry (aeration; adding CaCO<sub>3</sub>; adding a carbon source). 20% coverage of islands is optimal for aerobic basins. 100% cover is optimal for anaerobic basins or aerobic basins where there is artificial aeration. The design the FTW and the control of basin water chemistry is essential for optimising treatment efficiencies. The passive use of activated carbon within layers of floating islands is unlikely to be cost effective.*

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**Exploring hydrobiogeochemical processes of floating  
treatment wetlands in a subtropical stormwater wet  
detention pond**

<b>Type</b>	Journal Article
<b>Author</b>	Chang, N.B, Z. Xuan. Z Marimon, K. Islam, P. Wanielista
<b>Publication</b>	Ecological Engineering
<b>Volume</b>	54
<b>Pages</b>	66-76
<b>Date</b>	2013

**Notes:**

This peer-reviewed article covers a study of BioHaven islands and Beemat products that was reported in a previous University of Central Florida report.

**Abstract:**

*Floating treatment wetland (FTW) is one of the emerging best management practices (BMPs) for stormwater treatment where*

macrophytes provide a suitable root-zone environment for microorganisms that allow the plants to remove nutrients through direct uptake into their tissue. In this study, four floating mats with native Florida aquatic macrophytes were deployed in a 340 m<sup>2</sup> subtropical stormwater wet detention pond. A fountain in the pond and peat moss used to hold the substrate for plant species on the floating mats are both assumed to add nutrients to the water column. The aim of this study was to evaluate the performance of nutrient removal through the four floating mats and explore associated effects of simultaneous hydrological and biological controls related to various hydrobiogeochemical processes for nutrient removal in a multimedia pond environment. Nutrient concentrations in both inlet and outlet were monitored continuously over 13 months, with episodic (storm events) and routine (non-storm events) sampling plans carried out in parallel to justify the efficacy of the FTWs. Nutrient values within the water column and the sediment were compared before (Phase I) and after (Phase II) the deployment of the FTWs to prove the proposed hypotheses. An additional phase (Phase III) after the removal of the FTWs was added to enhance the understanding of ecosystem response. For non-storm events, phosphorus removal was substantial because of the increase in the initial concentrations, presumably due to resuspension of nutrients into the water column from the fountain operation; about 47.7% total phosphorus (TP) and 79.0% orthophosphate (OP) were removed. The removal rates of total nitrogen (TN), nitrite- and nitrate-nitrogen (NO<sub>x</sub>-N = NO<sub>2</sub>-N + NO<sub>3</sub>-N), and ammonia-nitrogen (NH<sub>3</sub>-N) were also calculated as 15.7, 20.6, and 51.1%, respectively. Without the uptake by plants, the nutrient removal decreased to different degrees when comparing those in non-storm events during Phase II. Considering plant species, nutrient uptake and assimilation by soft rush (*Juncus effusus*) was much higher than that by pickerelweed (*Pontederia cordata*) through both leaves and roots in this case. For soft rush, uptake rate in spring is much higher than that in fall. About 77.0 g N and 8.8 g P were removed from pond water via uptake and assimilation during the second phase. Despite organic nitrogen accumulation due to the pickerelweed leaf debris sedimentation, the organic nitrogen concentration in pond water was still kept at a low level, which implies that the ecosystem is capable of efficiently managing the withered plants and circulating nutrients.

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### **Floating Treatment Wetland Retrofit to Improve Stormwater Pond Performance for Suspended Solids, Copper and Zinc.**

<b>Type</b>	Journal Article
<b>Author</b>	Borne, Karine E., E.A. Fassman, C.C. Tanner
<b>Publication</b>	Ecological Engineering
<b>Volume</b>	54
<b>Pages</b>	173-182
<b>Date</b>	2013

#### **Notes:**

This peer-reviewed article summarizes a sophisticated stormwater study that utilized automatic samplers, remote flow measurement sensors, complex math analyses, etc.

The study shows that, when plant roots are long enough to reach near the bottom of a pond and water is flowing through the pond, results are good. There was a plant die-off observed at the end of summer, which produced toxic conditions beneath the mat. This was attributed to severe deoxygenation, which would have affected biofilm performance as well. FTW coverage of the pond was 50%.

This was a controlled study with two parallel ponds. The pond with FTW had 41% better removal for TSS than the control pond, 40% for particulate ZN, and 39% for particulate copper.

#### **Abstract:**

*A field trial study with side-by-side monitoring of two parallel stormwater treatment ponds, one of which contained a floating treatment wetland (FTW), has been carried out to assess the benefit of retrofitting a conventional retention pond with a FTW. Inflow and outflow event mean concentrations (EMCs) were quantified and used to assess the overall pollutant removal efficiency of each system. Findings show that a FTW can significantly improve the runoff water quality and thus reduce the impact on the receiving environment. The present study reveals that a pond retrofit with a FTW would be more efficient than a conventional retention pond, exhibiting a 41% (for total suspended solids – TSS), 40% (for particulate zinc – PZn), 39% (for particulate copper – PCu) and 16% (for dissolved copper – DCu) lower effluent EMC. Physical entrapment of the particulate pollutants into the roots' biofilm seems to be a significant removal pathway, which could be impacted by the inflow volume. Due to higher humic content, lower dissolved oxygen and more neutral water column pH induced by the FTW, there was increased potential for adsorption processes and/or precipitation as*

insoluble copper sulphides, in addition to the direct Cu uptake by the plants. The dissolved zinc (DZn) inlet EMCs, which already met the Australian and New Zealand Environment Conservation Council (ANZECC) water quality guidelines and could correspond to an irreducible concentration of the system, were too low to differentiate the performance of either pond.

<http://hdl.handle.net/2292/21002>

## Evaluation of floating treatment wetlands as retrofits to existing stormwater retention ponds

<b>Type</b>	Journal Article
<b>Author</b>	Winston, R.J., W.F. Hunt, S.G. Kennedy, L.S. Merriman, J. Chandler, D. Brown
<b>Publication</b>	Ecological Engineering
<b>Volume</b>	54 (2013)
<b>Pages</b>	254-265
<b>Date</b>	March 2013

### Notes:

This peer-reviewed article covers the study previously reported by William Hunt, et al.

### Abstract:

Thousands of existing wet retention ponds have been built across the United States, primarily for the mitigation of peak flow and removal of sediment. These systems struggle to mitigate soluble nutrient loads from urban watersheds. A simple retrofit for improvement of pond performance for nitrogen and phosphorus removal could become popular. Floating treatment wetlands (FTWs), one such retrofit, are a hydroponic system that provides a growing medium for hydrophytic vegetation, which obtain nutrients from the stormwater pond. Installation of FTWs does not require earth moving, eliminates the need for additional land to be dedicated to treatment, and does not detract from the required storage volume for wet ponds (because they float). To test whether FTWs reduce nutrients and sediment, two ponds in Durham, NC, were monitored pre- and post-FTW installation. At least 16 events were collected from each pond during both monitoring periods. The distinguishing characteristic between the two ponds postretrofit was the fraction of pond surface covered by FTWs; the DOT pond and Museum ponds had 9% and 18%, respectively, of their surface area covered by FTWs. A

very small fraction of N and P was taken up by wetland plants, with less than 2% and 0.2%, respectively, of plant biomass as N and P.

### Temperature

measurements at three depths below FTWs and at the same depths in open water showed no significant difference in mean daily temperatures, suggesting little shading benefit from FTWs. The two ponds produced effluent temperatures that exceeded trout health thresholds. Both the pre- and post-FTW retrofit ponds performed well from a pollutant removal perspective. One pond had extremely low total nitrogen (TN) effluent concentrations (0.41 mg/L and 0.43 mg/L) during both pre- and post-FTW retrofit periods, respectively. Floating treatment wetlands tended to improve pollutant capture within both ponds, but not always significantly. Mean effluent concentrations of TN were reduced at the DOT pond from 1.05 mg/L to 0.61 mg/L from pre- to post-retrofit. Mean total phosphorus (TP) effluent concentrations were reduced at both wet ponds from pre- to post-retrofit [0.17 mg/L to 0.12 mg/L (DOT pond) and 0.11 mg/L to 0.05 mg/L (Museum pond)]. The post-retrofit effluent concentrations were similar to those observed for bioretention cells and constructed stormwater wetlands in North Carolina. The DOT pond showed no significant differences between pre- and post-retrofit effluent concentrations for all nine analytes. The Museum pond had a statistically significant improvement post-retrofit (when compared to the pre-retrofit period) for both TP and total suspended solids (TSS). Wetland plant root length was measured to be approximately 0.75 m, which had the benefit of stilling water flow, thereby increasing sedimentation. Results suggested that greater percent coverage of FTWs produced improved pollutant removal.

## Floating treatment wetland aided remediation of nitrogen and phosphorus from simulated stormwater runoff

<b>Type</b>	Journal Article
<b>Author</b>	White, S.A., M.M. Cousins
<b>Publication</b>	Ecological Engineering
<b>Volume</b>	61 (2013)
<b>Pages</b>	207-215
<b>Date</b>	2013

### Notes:

A peer-reviewed article of a Beemat study conducted at Clemson University.

**Abstract:**

*Floating treatment wetlands are potential alternatives to traditional constructed wetlands for remediating nutrient-rich water. This study examined the remediation efficacy of floating treatment wetlands planted with Canna flaccida and Juncus effusus in a replicated trough system over two growing seasons at two nutrient loading rates. Plant growth parameters were measured on a biweekly basis, and water quality parameters were monitored weekly. Plant shoots and roots were harvested at the end of the first growing season, and biomass was dried, ground, and analyzed for nutrient content. Juncus plants fixed  $28.5 \pm 3.4$  gN per m<sup>2</sup> and  $1.69 \pm 0.2$  gP per m<sup>2</sup>, while Canna fixed  $16.8 \pm 2.8$  gN per m<sup>2</sup> and  $1.05 \pm 0.2$  g P per m<sup>2</sup>. More N and P were fixed in the below-mat biomass of both species than in the above-mat biomass, thus whole-plant harvest may be a critical management strategy for floating treatment wetlands. During the first season, when nutrient addition rates simulated stormwater loading conditions, effluent nutrient concentrations were very low and averaged  $0.14 \pm 0.04$  mgL<sup>-1</sup> total N and  $0.02 \pm 0.01$  mgL<sup>-1</sup> total P. During the second season, nutrient-loading rate into treatment wetlands was doubled to simulate a more nutrient-rich runoff, and effluent nutrient concentrations averaged  $0.79 \pm 0.3$  mgL<sup>-1</sup> total N and  $0.12 \pm 0.03$  mgL<sup>-1</sup> total P. Floating treatment wetlands may prove most effective in low nutrient environments where it is necessary to polish water quality to extremely low P concentrations.*

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**Constructed Wetlands with Floating Emergent Macrophytes: An Innovative Stormwater Treatment Technology**

Type	Journal Article
Author	Headley, T.R. and C.C. Tanner
Publication	Critical Reviews in Environmental Science and Technology
Volume	42
Pages	2261-2310
Date	2012

**Notes:**

This peer reviewed article describes various uses for FTWs (stormwater, sewage, acid mine drainage, animal waste, eutrophic lakes, and water

supply reservoirs) and focuses on stormwater. Numerous macrophyte species are described. Nutrient removal data for numerous studies and numerous parameters are compiled. This paper provides an excellent summary of research methods and results conducted by major researchers in the field of FTWs.

**Abstract:**

*The treatment of urban stormwater poses numerous technical and operational challenges, particularly due to the intermittent and highly variable nature of hydrologic and pollutant inputs. Floating emergent macrophyte treatment wetlands (FTWs) are a hybridization of ponds and wetlands that offer potential advantages for treatment of these highly variable flows. FTWs utilize rooted, emergent macrophytes growing on a mat or raft floating on the surface of the water rather than rooted in the sediments. Thus, they can tolerate the widely fluctuating water depths typical of stormwater systems, without the risk of the plants drowning. The roots hang beneath the floating mat and provide a large surface area for biofilm attachment. The authors provide a review of the FTW concept, structure, function, and treatment efficiency reported to date and discuss the potential advantages of this emerging technology for stormwater applications. Although still limited, the available data from mesocosm and pilot studies on removal of key pollutants such as organic matter, suspended solids, nutrients, and metals shows that they can significantly enhance performance of pond systems, and provide similar or better performance than surface flow wetlands for a range of polluted waters. Further studies are needed to verify the apparent potential of FTWs treating stormwater at full scale.*

<http://dx.doi.org/10.1080/10643389.2011.574108>

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**The Ability of Vegetated Floating Islands to Improve Water Quality in Natural and Constructed Wetlands, A Review**

Type	Journal Article
Author	Masters, B.
Publication	Water Practice & Technology
Volume	Vol 7 No. 1

**Pages** n/a  
**Date** 2012

**Notes:**

This peer-reviewed article provides a detailed overview of the history and various mechanisms of FTWs for water quality improvement, and provides summaries of data obtained by FII in laboratory and field-scale tests. The report also lists suppliers of FTWs worldwide and has a comprehensive reference list of technical articles describing various aspects of FTWs.

**Abstract:**

*Constructed and natural wetlands are widely used to improve many water quality parameters. Vegetated floating islands (VFIs) placed on the surface of these wetlands significantly enhance the efficiency of natural processes that reduce nutrients, suspended solids, heavy metals and other pollutants.*

*Pollutant reduction in VFIs, particularly nutrients such as nitrogen and phosphorous, occurs primarily through the actions of bacterial biofilms growing within the island matrix and on plant roots hanging below the islands. Direct uptake of nutrients by plants is minor, although plants are essential as they provide additional substrate for biofilm development while supplying oxygen and carbon for use by the bacteria.*

*Nitrogen-based nutrients are primarily removed from wetlands as nitrogen gas. Phosphorous is mostly deposited as organic-rich sediment which accumulates within or beneath the floating islands. This material can become anoxic and return its contained phosphorous to the water column, making it biologically available for*

*algal or bacterial blooms that degrade water quality. Physical removal of this P-rich material is an essential wetland management action. VFIs can remove phosphorous at up to 4.6 g/m<sup>2</sup>/day and ammonia at up to 8.1 g/m<sup>2</sup>/day with simultaneous*

*denitrification of nitrate to nitrogen gas. VFIs can significantly increase the efficiency of pollutant removal from natural and constructed wetlands.*

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## Floating Treatment Wetlands for Domestic Wastewater Treatment

<b>Type</b>	Journal Article
<b>Author</b>	Faulwetter, J.L., M.D. Burr, A.B. Cunningham, F.M. Stewart, A.K. Camper and O.R. Stein
<b>Publication</b>	Water Science & Technology
<b>Volume</b>	64.10
<b>Pages</b>	2089-2095
<b>Date</b>	2011

**Notes:**

A peer-reviewed report that describes the DNA analysis of the bacteria types that were studied in the second Montana-based MBRCT grant. The DNA was identified by denaturing gradient gel electrophoresis (DGGE) by targeting specific functional genes from bacteria samples collected at the top, center, and bottom of island matrix growing on simulated wastewater.

**Abstract:**

*Floating islands are a form of treatment wetland characterized by a mat of synthetic matrix at the water surface into which macrophytes can be planted and through which water passes. We evaluated two matrix materials for treating domestic wastewater, recycled plastic and recycled carpet fibers, for chemical oxygen demand (COD) and nitrogen removal. These materials were compared to pea gravel or open water (control). Experiments were conducted in laboratory scale columns fed with synthetic wastewater containing COD, organic and inorganic nitrogen, and mineral salts. Columns were unplanted, naturally inoculated, and operated in batch mode with continuous recirculation and aeration. COD was efficiently removed in all systems examined (>90% removal). Ammonia was efficiently removed by nitrification. Removal of total dissolved N was ~50% by day 28, by which time most remaining nitrogen was present as NO<sub>3</sub>-N. Complete removal of NO<sub>3</sub>-N by denitrification was accomplished by dosing columns with molasses. Microbial communities of interest were visualized with denaturing gradient gel electrophoresis (DGGE) by targeting specific functional genes. Shifts in the denitrifying community were observed post-molasses addition, when nitrate levels decreased. The conditioning time for reliable nitrification was determined to*



be approximately three months. These results suggest that floating treatment wetlands are a viable alternative for domestic wastewater treatment.

## The Taxonomy of Treatment Wetlands: A Proposed Classification and Nomenclature System

Type	Journal Article
Author	Headley, T.R. and N. Fonder
Publication	Journal of Environmental Engineering
Volume	(in press)
Pages	n/a
Date	2011

### Notes:

This peer-reviewed paper provides good descriptions and pictures of the various types of treatment wetlands.

### Abstract :

*This paper proposes a structured foundation for classifying and naming different treatment wetland (TW) design alternatives, based on observable physical design traits. A classification hierarchy is organised like a polychotomous key, from general classification criteria to wetland type identification. Three characteristics are typical of all TW: the presence of macrophytic vegetation; the existence of water-logged or saturated substrate conditions for at least part of the time; and inflow of contaminated water with constituents to be removed. Treatment Wetlands are further classified based on hydrology and vegetation characteristics. Hydrological traits relate to water position, flow direction, degree of saturation and position of influent loading. Based on the predominant position of water in the system, two main groups are identified: those with Surface Flow above a benthic substrate and those with Subsurface Flow through a porous media. The systems with surface flow are divided into three standard types, differentiated by vegetation type: Surface Flow (SF), Free-Floating Macrophyte (FFM), and Floating Emergent Macrophyte (FEM) TWs. Subsurface flow systems always contain sessile emergent macrophytes and are divided into four standard types, based on flow direction: Horizontal Sub-Surface Flow (HSSF), Vertical Flow (VF), Up Flow (UF) and Fill and Drain (FaD) TWs. Standard types are described with their main applications. Associated variants are identified. An overview of*

*intensified variants, which have elevated energy, chemical or operational inputs in order to increase efficiency or overcome process limitations, is also provided.*

## Components of floating emergent macrophyte wetlands influencing removal of stormwater pollutants

Type	Journal Article
Author	Tanner, C.C. and T.R. Headley
Publication	Ecological Engineering
Volume	37
Issue	3
Pages	474-486
Date	2011

### Notes:

This peer-reviewed article describes the findings of tank-scale controlled experiments comparing FTWs planted with and without macrophytes for the removal of metals, phosphorus, and turbidity. The study examines the contribution of each of the major constituents of the FTWs.

### ABSTRACT

*Floating treatment wetlands planted with emergent macrophytes (FTWs) provide an innovative option for treating urban stormwaters. Emergent plants grow on a mat floating on the water surface, rather than rooted in the bottom sediments. They are therefore able to tolerate the wide fluctuations in water depths that are typical of stormwater ponds. To better understand the treatment capabilities of FTWs, a series of replicated (n = 3) mesocosm experiments (12×0.7m<sup>3</sup> tanks using 0.36m<sup>2</sup> floating mats) were conducted over seven day periods to examine the influence of constituent components of FTWs (floating mat, soil media, and four different emergent macrophyte species) for removal of copper, zinc, phosphorus and fine suspended solids (FSS) from synthetic stormwater. The presence of a planted floating mat significantly (P < 0.05) improved removal of copper (>6-fold), fine suspended particles (#3-fold reduction in turbidity) and dissolved reactive P (in the presence of FSS) compared to the control. Living*

plants provided a large submerged root surface-area (4.6–9.3m<sup>2</sup> of primary roots m<sup>-2</sup> mat) for biofilm development and played a key role in the removal of Cu, P and FSS. Uptake of Cu and P into plant tissues during the trials could only account for a small fraction of the additional removal found in the planted FTWs, and non-planted floating mats with artificial roots providing similar surface area generally did not provide equivalent benefits. These responses suggest that release of bioactive compounds from the plant roots, or changes in physico-chemical conditions in the water column and/or soils in the planted FTWs indirectly enhanced removal processes by modifying metal speciation (e.g. stimulating complexation or flocculation of dissolved fractions) and/or the sorption characteristics of biofilms. The removal of dissolved zinc was enhanced by the inclusion of a floating mat containing organic soil media, with reduced removal when vegetated with all except one of the test species. The results indicate that planted FTWs are capable of achieving dissolved Cu and Zn mass removal rates in the order of 5.6–7.7mgm<sup>-2</sup> d<sup>-1</sup> and 25–104mgm<sup>-2</sup> d<sup>-1</sup>, respectively, which compare favourably to removal rates reported for conventional surface flow constructed wetlands treating urban stormwaters. Although not directly measured in the present study, the removal of particulate-bound metals is also likely to be high given that the FTWs removed approximately 34–42% of the turbidity associated with very fine suspended particulates within three days. This study illustrates the promise of FTWs for stormwater treatment, and supports the need for larger-scale, longer-term studies to evaluate their sustainable treatment performance.

## The Effects of Artificial Floating Wetlands on Water Quality in a Eutrophic Lake

<b>Type</b>	Master's Thesis
<b>Author</b>	Jangrell-Bratli, A. S.
<b>Publication</b>	University of Florida St. Petersburg
<b>Volume</b>	n/a
<b>Pages</b>	n/a
<b>Date</b>	July 2011

### Notes:

This 160-page thesis describes the results of a pond-scale study using FTWs comprised of plastic flotation pipe and netting, with macrophytes. This study is related to the 2011 study by J.A. Vogel.

## Effects of Vegetation, Season and Temperature on the Removal of Pollutants in Experimental Floating Treatment Wetlands

<b>Type</b>	Journal Article
<b>Author</b>	Van de Moortel, A.M.K., E. Meers, N. De Pauw, F.M.G. Tack
<b>Publication</b>	Water Air Soil Pollution
<b>Volume</b>	212
<b>Pages</b>	281-297
<b>Date</b>	Feb 2010

### Notes:

This peer-reviewed article describes a comparative study of FTWs with and without plants.

### Abstract:

The research and interest towards the use of constructed floating wetlands for (waste)water treatment is emerging as more treatment opportunities are marked out, and the technique is applied more often. To evaluate the effect of a floating macrophyte mat and the influence of temperature and season on physico-chemical changes and removal, two constructed floating wetlands (CFWs), including a floating macrophyte mat, and a control, without emergent vegetation, were built. Raw domestic wastewater from a wastewater treatment plant was added on day 0. Removal of total nitrogen, NH<sub>4</sub>-N, NO<sub>3</sub>-N, P, chemical oxygen demand (COD), total organic carbon and heavy metals (Cu, Fe, Mn, Ni, Pb and Zn) was studied during 17 batch-fed testing periods with a retention time of 11 days (February–March 2007 and August 2007–September 2008). In general, the CFWs performed better than the control. Average removal efficiencies for NH<sub>4</sub>-N, total nitrogen, P and COD were respectively 35%, 42%, 22% and 53% for the CFWs, and 3%, 15%, 6% and 33% for the control. The pH was significantly lower in the CFWs (7.08± 0.21) than in the control (7.48±0.26) after 11 days. The removal efficiencies of NH<sub>4</sub>-N, total

nitrogen and COD were significantly higher in the CFWs as the presence of the floating macrophyte mat influenced positively their removal. Total nitrogen,  $\text{NH}_4\text{-N}$  and P removal was significantly influenced by temperature with the highest removal between 5°C and 15°C. At lower and higher temperatures, removal relapsed. In general, temperature seemed to be the steering factor rather than season. The presence of the floating macrophyte mat restrained the increase of the water temperature when air temperature was > 15°C. Although the mat hampered oxygen diffusion from the air towards the water column, the redox potential measured in the rootmat was higher than the value obtained in the control at the same depth, indicating that the release of oxygen from the roots could stimulate oxygen consuming reactions within the root mat, and root oxygen release was higher than oxygen diffusion from the air.

### Floating Treatment Wetlands: An Innovative Option for Stormwater Quality Applications

<b>Type</b>	Conference Article
<b>Author</b>	Headley, T.R. and C.C. Tanner
<b>Publication</b>	11 <sup>th</sup> International Conference on Wetland Systems for Water Pollution Control (India)
<b>Volume</b>	Nov 1-7
<b>Pages</b>	1101-1106
<b>Date</b>	2008

#### Notes:

This peer-reviewed article is a short version of the 2012 report by Headley and Tanner (listed below). It describes various types of FTWs with macrophytes.

#### ABSTRACT

*Floating Treatment Wetlands (FTWs) are an innovative variant of the more traditional constructed wetland and pond technologies that offer great potential for treatment of urban stormwaters. FTWs employ rooted, emergent macrophytes (similar to those used in surface and subsurface flow wetlands) growing on a mat floating on the surface of the water rather than rooted in the sediments. Thus, they can tolerate the wide water depth fluctuations typical in stormwater systems, without the risk of the plants becoming inundated and stressed. In many aspects, FTWs are a hybrid between a pond and a wetland; they behave hydraulically similar to a stormwater detention*

*pond, whilst imparting similar treatment processes to that of a wetland. The plant roots hang beneath the floating mat and provide a large surface area for biofilm growth which forms an important part of the treatment reactor. This paper provides a review of the FTW concept, structure and function, and discusses some of the potential advantages of this emerging technology for stormwater applications.*

### Purification of nitrate-rich agricultural runoff by a hydroponic system

<b>Type</b>	Journal Article
<b>Author</b>	Yang, Z., S. Zheng, J. Chen, M. Sun
<b>Publication</b>	Bioresource Technology
<b>Volume</b>	99 (2008)
<b>Pages</b>	8049 - 8053
<b>Date</b>	April 2008

#### Notes:

Nutrient removal in runoff water was studied . Young O. javanica seedlings were evenly transplanted to 4-cm thick foam sheets that fully covered the overall water surface in the floating rafts.

#### Abstract:

*The purification of nitrate-rich agricultural runoff by a floating-raft (FR) hydroponic system was investigated at 3-, 2- and 1-d hydraulic retention times (HRTs) with particular emphasis on nitrogen conversion and removal through the system. The FR system has a dissolved oxygen (DO) environment similar to the horizontal subsurface flow system, generally 0.00 mg L<sup>-1</sup> that facilitates denitrification. An efficient nitrate-nitrite-nitrogen ( $\text{NO}_x\text{-N}$ ) removal, 91%, 97% and 71% on average at 3-, 2- and 1-d HRT, respectively, was frequently achieved. The mean retentions were 17–47% for chemical oxygen demand, 31–64% for total nitrogen, and 8–15% for total phosphorus for the FR system. Mass balance analysis implied that the detectable DO concentration in the reactor, as low as 0.7 mg L<sup>-1</sup>, played a very important role in the conversion and removal of  $\text{NH}_3\text{-N}$  and  $\text{NO}_x\text{-N}$ , which finally affected the  $\text{NO}_x\text{-N}$  removal at 3-d HRT.*

## Floating Islands as an Alternative to Constructed Wetlands for Treatment of Excess Nutrients from Agricultural and Municipal Wastes -- Results of Laboratory-Scale Tests

<b>Type</b>	Journal Article
<b>Author</b>	Stewart, F.M., T. Mulholland, A. Cunningham, B. Kania, M. Osterlund
<b>Publication</b>	Land Contamination and Reclamation
<b>Volume</b>	16
<b>Number</b>	1
<b>Pages</b>	25-33
<b>Date</b>	February 2008

### Notes:

This peer-reviewed article describes several of the tank-scale FTW experiments that measured bacterial biofilm removal of nitrate, ammonium and phosphate, and compares these removal rates to those achieved by other researchers, who were primarily focused on plant-based removal of nutrients on FTWs.

<http://www.floatingislandinternational.com/wp-content/plugins/fii/research/9.pdf>

### Abstract

*Constructed wetlands are recognized as effective mechanisms of water treatment and are employed in a variety of applications. Wetlands comprise diverse and complex systems of interacting plants and animals that remove contaminants from the water column by mechanical filtration and biochemical conversion. A major component of the wetland environment is microbial, with bacteria and other microorganisms proliferating upon all available submerged surfaces (i.e. substrate). In these wetland environments, microbial activity is limited by substrate surface area and nutrient flux. Consequently, the microbial contribution to wetland efficacy can be improved by increasing a wetland's substrate surface area and increasing water circulation rates through that substrate. Various studies have investigated the use of floating wetland platforms to enhance wetland capacity; however, none of those studies has determined the specific contributions of microbes. In our study, we*

*quantified the microbial component of BioHaven® Floating Islands for aerobic removal of ammonium, anoxic removal of nitrate, and simultaneous aerobic/anoxic removal of ammonium, nitrate and phosphate. This study establishes tank-scale standards to which other microbial data can be compared. In doing this, it has been determined that the microbes growing within a unit volume of BioHaven® Floating Island material are capable of removing 10 600 mg of nitrate per day, 273 mg of ammonium per day, and 428 mg of phosphate per day, where the unit island volume is defined as having a top surface area of 1.0 ft<sup>2</sup> and a thickness of 0.6 ft.*

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## (2) Articles Published in Professional and Trade Magazines

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### Floating Treatment Wetlands Improve Stormwater Quality

<b>Type</b>	Professional Magazine Article
<b>Author</b>	Reinsel, Mark
<b>Publication</b>	Environmental Science and Engineering
<b>Volume</b>	Volume 26, No. 3 May/June 2013
<b>Pages</b>	40-44
<b>Date</b>	2013

### Notes:

This article provides an overview of case studies in North Carolina and Montana, and provides removal rate and concentration data for eight common pollutants associated with stormwater.

<http://ese.dgtlpub.com/2013/2013-06-30/home.php>

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## Floating Wetlands Help Boost Nitrogen Removal in Lagoons

<b>Type</b>	Trade Magazine Article
<b>Author</b>	Reinsel, M.
<b>Publication</b>	WaterWorld
<b>Contract</b>	June
<b>Pages</b>	n/a
<b>Date</b>	2012

### Notes:

This article gives a short summary of removal of ammonia, nitrate, and some other nutrients at Rehberg Ranch (MT) , Wiconisco (PA) , McLean's Pit (NZ) and the MBRCT test ponds (MT).

<http://www.waterworld.com/articles/print/volume-28/issue-6/editorial-features/floating-wetlands-help-boost-nitrogen-removal-in-lagoons.html>

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## Wesstown Lake: Floating Wetland Islands

<b>Type</b>	Trade Magazine Article
<b>Author</b>	Lubnow, F.
<b>Publication</b>	Lakeline
<b>Volume</b>	Spring
<b>Pages</b>	31-35
<b>Date</b>	2012

### Notes:

This five-page article describes the phosphorus uptake mechanisms in FTWs (plants, microbes, filtration of particles, moving up the food chain). In a first pond experiment with FTWs, uptake of P and N were estimated by analyzing plant mass and nutrient concentration in the plants. In a second pond experiment (Mermaid Pool, New Jersey) P uptake was measured for a range of inflow values before and after FTW installation. Graphical results are presented for P uptake at the inlet and outlet of Mermaid Pool during 2011.

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## Floating Islands for Tertiary Nutrient Removal and Circulators for Primary & Secondary Treatment at an STP

<b>Type</b>	Trade Magazine Article
<b>Author</b>	Ambulkar, A., S. Zeller and D. Klinger
<b>Publication</b>	Everything About Water
<b>Volume</b>	May
<b>Pages</b>	85-87
<b>Date</b>	2012

### Notes:

Photographs and descriptions of BioHaven FTWs at the Wiconisco site, with additional information related to Solar Bee circulators also deployed at the site.

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## Floating Treatment Wetlands Mitigate Lake Eutrophication

<b>Type</b>	Professional Magazine Article
<b>Author</b>	Reinsel, M.
<b>Publication</b>	Environmental Science & Engineering Magazine
<b>Volume</b>	May/June
<b>Pages</b>	38-41
<b>Date</b>	2012

### Notes:

This article describes how D.O. and temperatures were improved for fish habitat at Fish Fry Lake, Shepherd, Montana, using a Leviathan™ system.

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## Using Floating Islands for Tertiary Nutrient Removal

<b>Type</b>	Professional Magazine Article
<b>Author</b>	Ambulkar, A., S. Zeller and D. Klinger
<b>Publication</b>	Environmental Science and Engineering Magazine
<b>Volume</b>	Summer

**Pages** 24-27  
**Date** 2010

**Notes:**

A summary of the first pilot-scale deployment of BioHaven FTWs in a controlled test of wastewater treatment in a municipal lagoon setting at Wiconisco, PA. Measured parameters described in the article include BOD, TN, and TP.

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### **(3) Articles Published in Popular Magazines, Books or On-Line**

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#### **Innovative Alternative for Waste Water Impoundment Treatment**

**Type** On-Line Magazine Article  
**Author** Waguespack, Nicole (Martin Ecosystems)  
**Publication** Land and Water  
**Volume** May/June 2013  
**Pages** 41 - 44  
**Date** 2013

**Notes:**

This on-line article provides a description of the floating island project for an unaerated wastewater lagoon the Elayn Hunt Correctional Facility in Louisiana. Photographs of the islands at various stages of plant growth are included. Descriptions of island placement, maintenance and repairs, planted species, and numerical results are provided.

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#### **Fishing out Phosphorus**

**Type** On-Line Magazine Article  
**Author** Fox, Andrea  
**Publication** WEF News  
**Volume** Jan 21  
**Pages** 1-6

**Date** 2013

**Notes:**

A description of the “phosphorus-to-fish” process that is being managed by Bruce Kania at Fish Fry Lake in Shepherd, MT.

<http://news.wef.org/fishing-out-phosphorus>

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#### **Floating Treatment Wetlands Mitigate Lake Eutrophication**

**Type** On-Line Magazine Article  
**Author** Kania, B, M. Reinsel, F. Stewart  
**Publication** Water Online  
**Volume** August 14  
**Pages** 1-7  
**Date** 2012

**Notes:**

This article provides an overview of the stewardship at Fish Fry Lake in Shepherd MT, for the improvement of water quality and fishing. Descriptions of the Leviathan® system and plots of DO and temperature versus depth (before and after stewardship) are presented. A photo of Bruce Kania with a string of large perch is included.

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#### **Floating Islands – an alternative to urban wetlands**

**Type** Chapter in a book  
**Author** Hwang, L. and A. LePage  
**Publication** Wetlands – Integrating Multidisciplinary Concepts, (LePage, B.A. ed. Springer Netherlands)  
**Volume** n/a  
**Pages** n/a  
**Date** 2011

## Floating Treatment Wetlands: An Innovative Option for Stormwater Quality Applications

<b>Type</b>	Conference Article
<b>Author</b>	Headley, T.R. and C.C. Tanner
<b>Publication</b>	11 <sup>th</sup> International Conference on Wetland Systems for Water Pollution Control (India)
<b>Volume</b>	Nov 1-7
<b>Pages</b>	1101-1106
<b>Date</b>	2008

### Notes:

This peer-reviewed article is a short version of the 2012 report by Headley and Tanner (listed below). It describes various types of FTWs with macrophytes.

### ABSTRACT

*Floating Treatment Wetlands (FTWs) are an innovative variant of the more traditional constructed wetland and pond technologies that offer great potential for treatment of urban stormwaters. FTWs employ rooted, emergent macrophytes (similar to those used in surface and subsurface flow wetlands) growing on a mat floating on the surface of the water rather than rooted in the sediments. Thus, they can tolerate the wide water depth fluctuations typical in stormwater systems, without the risk of the plants becoming inundated and stressed. In many aspects, FTWs are a hybrid between a pond and a wetland; they behave hydraulically similar to a stormwater detention pond, whilst imparting similar treatment processes to that of a wetland. The plant roots hang beneath the floating mat and provide a large surface area for biofilm growth which forms an important part of the treatment reactor. This paper provides a review of the FTW concept, structure and function, and discusses some of the potential advantages of this emerging technology for stormwater applications.*

## (4) Reports

### Floating Treatment Wetland Technologies

<b>Type</b>	Unpublished Report for Distribution
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<b>Author</b>	Reinsel, Mark
<b>Publication</b>	Floating Island International, Inc
<b>Pages</b>	1-25
<b>Date</b>	November 2012

### Notes:

This report describes the various FII treatment alternatives (BioHavens, Leviathan, Coral, and BioSwales) and discusses design, installation, and costs.

## BioHaven technology: Where Human Endeavor and Nature Come Together

<b>Type</b>	Unpublished Report for Distribution
<b>Author</b>	FII Staff
<b>Publication</b>	Floating Island International, Inc
<b>Pages</b>	1-4
<b>Date</b>	September 2012

### Notes:

This article was prepared for the U.S. Navy. It provides an overview of FII, as well as a review of various applications for FTW technology. The article contains several photographs of FTWs in different settings around the world, including a tern nesting island, a Leviathan® stream channel, a framework for a circular FTW under construction, and a 21,000 sf archipelago in Singapore. The article also provides a future vision statement for the FTW products.

## Floating Wetland Systems for Nutrient Removal in Stormwater Ponds – FDOT Project BDK78 985-01

<b>Type</b>	University Project with Florida DOT Supervision – Final Report
<b>Project Manager</b>	Rick Renna, P.E., State Hydraulics Engineer
<b>Author</b>	Wanielista, M.P.; NB Chang, M. Chopra, Z. Xuan, K. Islam, Z. Marimon
<b>Publication</b>	n/a

**Date** September 2012

**Notes:**

This 182-page final report describes tank-scale and pond-scale experiments for BioHaven islands and Beemat products. The pond-scale experiments were affected by nutrient uptake by duckweed and algae in the controls. The study recommends giving a 12% credit for deploying FTWs in stormwater ponds. The report incorporates numerous photographs and numerical data.

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**Waterway Stewardship through Floating Islands**

<b>Type</b>	Unpublished Report for Distribution
<b>Author</b>	Reinsel, Mark, F. Stewart
<b>Publication</b>	Floating Island International, Inc
<b>Pages</b>	1-10
<b>Date</b>	June 2012

**Notes:**

This 10-page report provides an overview of floating treatment wetlands (FTWs). The article covers biofilm basics, nutrient removal mechanisms, a comparison of nutrient removal efficacy by FTWs compared to other stormwater BMP methods, and fishery enhancement by FTWs. A bullet list summary of important facts from Azim's periphyton ecology textbook is provided. A short discussion of the Fish Fry Lake case study is also included.

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**Final report: Evaluation of Floating Wetland Islands (FWIs) as a Retrofit to Existing Stormwater Detention Basins**

<b>Type</b>	Final Report
<b>Author</b>	Hunt, W.F; R.J. Winston, S.G. Kennedy
<b>Publication</b>	North Carolina DENR
<b>Contract</b>	1653
<b>Pages</b>	1-71

**Date** March 22, 2012

**Notes:**

This report describes research conducted on real-world stormwater ponds under controlled conditions by the University of North Carolina under a grant funded by the NC DENR. Measured parameters included TN, TP, and TSS. The data were statistically analyzed.

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**Control of Microbial Processes for Enhanced Water Treatment Using Floating Island Treatment Systems**

<b>Type</b>	Grant Final Report
<b>Author</b>	Cunningham, A.B., A. Camper, M. Burr and F.M. Stewart
<b>Publication</b>	Montana Board of Research and Commercialization Technology
<b>Date</b>	2010

**Notes:**

The final report for the second Montana-based MBRCT grant. The report includes data from controlled laboratory-scale studies at the Center for Biofilm Engineering at Montana State University. The lab experiments compared organic carbon, ammonium and nitrate removal in simulated wastewater for various matrix types including PET and recycled carpet fibers. The experiments also compared various aeration cycling regimes to optimize for combined aerobic and anoxic bacterial removal. DNA analysis was performed on the bacterial biofilms to determine how the nitrifiers and denitrifiers were distributed within the matrix columns.

The project also included field-scale components, which comprised a comparison of wind-electric and solar-electric-power for circulating and aerating outdoor islands. In addition, a 1300-sf island was installed in a wastewater lagoon in Billings, MT, and a controlled experiment was started that tracked removal of TN, TP, nitrate, ammonium, phosphate, and COD in an island lagoon and a control lagoon. Removal data are presented in the report.



This report is available on the FII website.

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### **Floating Vegetated Islands for Stormwater Treatment: Removal of Copper, Zinc and Fine Particulates**

<b>Type</b>	Report
<b>Author</b>	Headley, T.R. and C.C. Tanner
<b>Publication</b>	NIWA Client Report HAM2007-175
<b>Source</b>	Auckland (NZ) Regional Council
<b>Pages</b>	1-28
<b>Date</b>	Nov 2007

#### **Notes:**

The first part of this report is a study of suitable NZ native plant species suitable for use on FTWs. The second part of this report describes experiments that measured removal rates of copper, zinc, and fine particulates in 1 m<sup>3</sup> test tanks run in triplicate. Numerical data of removal rates are presented in the report. The report provides a good description of a well-run experiment and contains photographs of the tanks, FTWs, plant tops and roots.

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### **Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review**

<b>Type</b>	Report
<b>Author</b>	Headley, T.R. and C.C. Tanner
<b>Publication</b>	NIWA Client Report HAM2006-123
<b>Source</b>	Auckland (NZ) Regional Council
<b>Pages</b>	1-100
<b>Date</b>	Nov 2006

#### **Notes:**

This report provides descriptions and photographs of a wide range of FTWs that were commercially available in 2006, including the FII products. It does not include experimental results that were obtained after 2006 (see the 2011 and 2012 papers for more recent data).

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